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THESIS

DESIGN AND OPERATIONAL ASPECTS OF AUTONOMOUS UNMANNED COMBAT AERIAL VEHICLES

by

Arne Baggesen

September 2005

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A family of advanced weapon systems that deserves special attention comprises aerial autonomous weapons called Unmanned Combat Aerial Vehicles (UCAVs), which are characterized by the ability to loiter in the target area, sense the targets, acquire the targets, and then engage them. Modeling this combination of capabilities in a specific operational setting is necessary for addressing design and operational issues of this weapon. This work focuses on the development of an analytic probability model that captures key aspects of the autonomous weapon systems' engagement process. Special attention is given to simultaneous attack occurrences, imperfect battle damage assessment, and attack coordination properties.

The model is a continuous-time Markov Chain and for its implementation a state generator and an algorithm that computes the transition and limiting probabilities has been developed and programmed in Java based software. The Markov-model derives values for several measures of effectiveness (MOEs), and the average engagement time.

Different operational scenarios and design configurations are examined in a sample analysis to demonstrate the model's capabilities. Tradeoffs among sensing, data processing capabilities, vulnerability and lethality of UCAVs are explicitly represented with respect to selected MOEs.

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DESIGN AND OPERATIONAL ASPECTS OF AUTONOMOUS UNMANNED COMBAT AERIAL VEHICLES ALL CAPS

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ABSTRACT

A family of advanced weapon systems that deserves special attention comprises aerial autonomous weapons called Unmanned Combat Aerial Vehicles (UCAVs), which are characterized by the ability to loiter in the target area, sense the targets, acquire the targets, and then engage them. Modeling this combination of capabilities in a specific operational setting is necessary for addressing design and operational issues of this weapon. This work focuses on the development of an analytic probability model that captures key aspects of the autonomous weapon systems' engagement process. Special attention is given to simultaneous attack occurrences, imperfect battle damage assessment, and attack coordination properties.

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ACRONYMS, ABBREVIATIONS AND SYMBOLS

A. LIST OF ACRONYMS AND ABBREVIATIONS:

ACTD	Advanced Concept Technology Demonstration
AIM-9X	Next Generation Sidewinder Missile
ATD	Automatic Target Detection
ASRAAM	Advanced Short Range Air-to-Air Missile
ATR	Automatic Target Recognition
BAT	Brilliant Anti-Armor Submunition
BDA	Battle Damage Assessment
BMDO	Ballistic Missile Defense Organization
BPI	Boost Phase Interception
CBW	Chemical/Biological Warfare
CMD	Cruise Missile Defense
CONOPS	Concept of Operations
COTS	Commercial Off the Shelf
CWMD	Countering Weapons of Mass Destruction
DARPA	US Defense Advanced Research Projects Agency
DSB	Defense Science Board
EMCON	Emission Control
ERE I	Expected Relative Effectiveness
ERE II	Expected Relative Efficiency
GPS	Global Positioning System
INS	Inertial Navigation System

JSF	Joint Strike Fighter
KKV	Kinetic Kill Vehicle
LADAR	Laser Detection and Ranging
LAM	Loitering Attack Missile
LOCAAS	Low Cost Autonomous Attack System
MOE	Measure Of Effectiveness
NET	Number of UCAVs to Exceed an Operational Threshold
PET	Probability to Exceed an Operational Threshold
PGM	Precision Guided Munition
ROEs	Rules of Engagement
SAB	Science Advisory Board
SAM	Surface to Air Missile
SDB	Small Diameter Bomb
SEAD	Suppression of Enemy Air Defense
SMT	Simultaneous Multi Targeting (of a single target)
SSKP	Single Shot Kill Probability
TBF	Time Between Failure
TBMD	Theatre Ballistic Missile Defense
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Aerial Vehicle
WASM	Wide Area Search Munition

B. LIST OF SYMBOLS:

λ	average detection rate
φ	average attrition (-removal-) rate
μ	1/average attack duration
χ	probability threshold
α	fraction of killed targets
T	total number of targets
M	initial number of valuable targets
N	initial number of UCAVs
m_x	number of targets simultaneously attacked by x UCAVs
n	number of searching UCAVs
r	probability to correctly receive and process an attack message
p	single shot kill probability (SSKP)
q_2	classification sensitivity –probability to correctly classify a valuable target
q_2	classification specificity –probability to correctly classify a non valuable target

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I. INTRODUCTION

A. INTRODUCTION

The evolution in air-to-ground and air-to-air warfare ranges from guns, unguided gravity bombs, and missiles to modern-day unmanned aerial vehicles (UAV) and precision guided munitions (PGM). UAVs are often regarded as an evolutionary step to new sensor platforms, predominantly in the reconnaissance and surveillance roles. Other payloads include electronic-warfare suites, communications-relay packages, munitions, submunitions and integrated warheads. Armed UAVs are often referred to as unmanned/uninhabited combat air vehicles (UCAVs). The distinctions among UAVs, UCAVs, and certain precision guided munitions (PGM) as wide area search munitions (WASM) are fuzzy and often depend on organization-specific policy and definitions. What all of these categories have in common is removing the human being from the platform or providing stand-off capabilities. This has technical and operational advantages in many dimensions, but also bequeaths new operational and ethical concerns.

The use of UAVs removes the risk of aircrew being killed, injured or captured if the vehicle is shot down or lost due to mechanical failure. Airframe designs can be smaller and lighter than their manned counterparts and can be designed for longer endurance. Also, UCAV platforms are cheaper to buy and operate, and require less expensive testing and training. These might be among the main advantages in future planning.

Modern UCAVs are navigated and guided by radar, video, infrared cameras, lasers, and Inertial Navigation Systems (INS) and aided by the satellite based Global Positioning System (GPS). The enhancement of sensor systems, processor units, decision making algorithms, and terminal seekers leads to autonomy for target acquisition, recognition, and attack. These capabilities, combined with inexpensive designs and operational opportunities, make UCAVs a disruptive technology on the battlefield. UCAVs enable war-fighters to attack targets with weapon systems that can operate in highly defended areas, and cause less collateral damage due to enhanced precision. There no longer seems to be a trade-off between own casualties and the effect of attacks. This is especially important for a society that is perceived as being less and less tolerant of high-casualty en-

gagements and collateral damage. The progress in commercial technologies, which continues to lower costs for UCAV systems, is another reason for the increasing interest in this type of weapon systems.

The transition from operating UAVs as sensor platforms to employing UCAVs as weapon carriers is a relatively minor technological step, but a major step in war fighting; it requires new operating concepts. An even bigger step is reflected in the aspect of autonomy, which leads to discussions transcending operational effectiveness and force-structure efficiency. Experts worry that the more abstract the use of weapon systems becomes, the more abstract the enemy becomes, and as humans recede from the battlefield as combatants, war will become more likely, not less (Clifford 2000). A more concrete discussion includes the shift of the attack decision responsibility from the war-fighter to the authority that approves the autonomous engagement and applicable rules of engagement (ROEs) for autonomous systems. Current technology is just mature enough for limited autonomous engagements and needs more improvement in the important areas of target discrimination, identification and attack coordination. Today, algorithms are still double-checked by man-in-the-loop doctrines. Autonomous technology is still not completely unleashed. For the near future, however, UCAV developers believe that the man-in-the-loop will be the weakest part of the weapon system because humans will be too slow for the decision-making cycle, causing underperformance and collateral damage. This argument seems reasonable when considering projected future engagement tactics. Almost always, it is planned that UCAVs will operate in swarm engagements, mainly in time-critical scenarios with the need for split-second decisions.

The challenge today is seen in the establishment of a new concept of operations (CONOPS) that includes doctrine for the proper use of the capabilities and responsibilities of this new generation of weapon systems. As a result of these considerations, more research is necessary on multiple areas of autonomous engagement. These include safety as well as performance-enhancing evaluations of UCAV design, engagement tactics, and doctrine.

B. RESEARCH FOCUS

Most future operational concepts utilize swarm tactics. Larger UAVs, missiles or aircrafts release small, expendable, fire and forget UCAVs, designed as Wide Area Search Munitions (WASMs) over the target area. The WASMs act in so-called hunter-killer packs to engage critical targets, high value targets, and targets of opportunity autonomously. The wide range of design factors and capabilities of such autonomously acting and interacting systems will most likely lead to a wide performance range for engagements in different scenarios.

While the importance of exploring these concepts is commonly accepted, the majority of work still concentrates on the performance of particular UCAVs in special scenarios. Most research is dedicated to the evaluation and simulation of the search and detection process, along with the target recognition and target identification processes. These factors are important for specifying and comparing the qualities of different UCAV designs, and give an estimate of the projected single system performance in a specific environment and tactical situation. Some research addresses the combined detection, classification, and attack process and evaluates the influence of imperfect battle-damage-assessment (BDA), but without considering the performance decreasing impact of simultaneous attacks on the same target. This concern is especially important for assessing the impact of battle intensity (detection frequency, attack duration, and UCAV attrition frequency) and the value of communication for attack coordination.

Therefore, we consider in our model the following design and operational factors: (i) detection rate, (ii) attack duration, (iii) weapon lethality, (iv) system vulnerability, (v) target recognition (BDA) capabilities, and (vi) communication capabilities. Additionally, scenario factors such as number of employed UCAVs, number of valuable targets in the target area, and number of false targets are considered.

Depending on the combination of the above listed factors, the effect of a single factor varies. This is true for engagements with single UCAVs, and gains more significance and complexity in swarm tactics. Therefore, more analytic work is needed to obtain deeper general insights into the complex interaction processes of these weapon systems in situations where swarm tactics are applied or when search areas of simultaneously em-

ployed UCAVs overlap. Detection, decision making, and attack processes are modeled as simply as possible (but no simpler) to address general issues of the importance of functional design factors on engagement effectiveness. Subsequently, the design, operational and scenario parameters are analyzed for their important effects on mission success. Next, implications for design and operational parameters are derived from the findings.

Because autonomous swarm tactics are analyzed, one major focus is the influence of attack coordination among multiple UCAVs on the mission success in scenarios where a target can be attacked by more than one UCAV. This influence is then compared to the influences of other design factors. The analysis also explores trade-off considerations as well as optimization approaches. The main contribution of this work is to formulate and implement a model that facilitates analysis. The analysis in this thesis intends to demonstrate the model capabilities and to gain some initial insights regarding design and operational factors.

The mathematical model consists of an absorbing continuous-time Markov-Chain capable of describing simultaneous multi-attack processes of several UCAVs for each target. Model extensions also implement imperfect BDA in the form of classification and imperfect coordination properties. This research introduces methods for identifying the most important parameters for a particular design configuration in a specific scenario. The insights are intended to support the evaluation and identification of the most (cost) effective improvements of design capabilities and as guidelines for engagement tactics.

C. MAIN FINDINGS

In this work we model simultaneous many-on-many engagements with continuous time Markov models that contain complex state descriptions and large state spaces.

The analysis shows that –within reasonable ranges of design and operational parameters,

(i) Coordination is largely a redundant feature. Its effect is strongly dependent on other design and operational factors.

(ii) The probability to correctly classify a non valuable target (specificity) is more critical to mission success than the probability to correctly classify a valuable target (sensitivity).

(iii) The performance decreasing effect of simultaneous attacks on the same target in swarm engagements is important enough to be addressed in operational and design considerations.

D. STRUCTURE OF THE THESIS AND CHAPTER OUTLINE

This thesis includes four chapters in addition to the introduction.

Chapter II presents literature review of current and proposed UCAV designs and references to related studies on UAVs and UCAVs. Previous modeling work on UCAV engagements is compared to the modeling approach of this thesis. This includes the basic assumptions that are used in our models. A set of measures of effectiveness (MOEs) is introduced at the end of this chapter.

In Chapter III, the Markov model and its extensions and modifications are presented.

In Chapter IV, we implement the Markov model and its extensions and perform a sample analysis for certain UCAV designs and scenarios. The analysis intends to illustrate the capabilities of the model and to provide general insights into the dynamics of many-on-many UCAV engagements.

Chapter V summarizes the research, presents the main results, and discusses possible future research.

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II. BACKGROUND

A. UCAVS

1. The Role of UCAVs in War Fighting

The UCAV technology leads to a large list of possible war fighting applications and emerging operational requirements. Some of these requirements are already realized in current technologies and in service; others are still about ten years ahead. While only a few areas of application are a result of force structure analysis and capability analysis, most applications were generated by the availability of the technology resulting from the continued use of demonstrators after field tests. Approaches to integrating the UCAV systems into existing force structure doctrine develop especially slowly (DSB, 2004; Defense Daily, 2005).

The main application of UAVs today is surveillance and reconnaissance, but in the last several years the trend has been established to arm UAVs and assign attack missions to this kind of UCAV. Still, man-in-the-loop control dominates the operation of UAVs/UCAVs, and only non-critical missions are conducted in autonomous mode (Sirak, 2002). The option of fully autonomous UCAV operation is quite new and not yet implemented operationally. While members of the armed forces have conducted studies of how engagements with UCAVs on future battlefields might look, established concrete concepts for these kinds of operations are still rare.

In a study on UAVs and UCAVs in 2004, the DOD Defense Science Board came to the conclusion that the acceleration of the introduction of UAVs into the force structure is necessary. Further, UCAVs must be considered as an integral part of the force structure and not only an “additional asset". Therefore, accelerated procurement and equipment of operational units are inevitable. In 1996, the USAF Scientific Advisory Board (SAB) conducted a study entitled "UAV Technologies and Combat Operations" (USAF SAB, 1996). The purpose was to define future applications for UAV and UCAV

systems, design requirements, and acquisition guidelines, and to describe scenarios and operational outlines. The study examined a wide range of potential roles and missions, including those involving combat.

The SAB identifies 22 different mission types for UAVs and UCAVs, including nine with high practical and technological potential for strengthening the current Air Force capability by complementing the existing force structure. Six of these nine involve armaments carriage: Countering weapons of mass destruction (CWMD), theatre ballistic/cruise missile defense (TBMD/CMD), fixed-target attack, moving-target attack, suppression of enemy air defense (SEAD), and air-to-air engagement. Referring to missions today dominated by manned aircraft, the study concludes that "UAVs have the potential to accomplish tasks that are now, for either survivability or other reasons, difficult for manned aircraft. These include counter-air (cratering runways and attacking aircraft shelters), destroying or functionally killing chemical/biological warfare (CBW) manufacturing and storage facilities, and SEAD." Further, the SAB identifies a new operational concept of TBMD, the boost phase interception (BFI), which is possible with UCAV technology. Considering the feasibility and likelihood of the identified mission types and tactics, the study states that most of the "…technologies necessary for platforms, are sufficiently mature to provide [as necessary identified] initial UAV capabilities" and that the limits to the employment of UCAVs lie in operational policy and procedural considerations. The reasons for this evaluation of the wide range of mission opportunities include the UCAVs' high persistency in the area of interest, stealth properties, and low cost. These can be achieved due to the human-independent design. Today, a decade later, UCAVs almost reach the human threshold of automatic tracking and target recognition that has, until now, prevented war-fighters from passing the attack decision to the system (Beal, 2000).

For the future, the USAF sees the initial operational role for UCAVs as a "first day of the war" SEAD weapon, forming an integral part of the force structure. UCAVs are tasked for lethal Suppression of Enemy Air Defenses, tactical jamming, real time surveillance, and Counter C^3I (command, control, communications and intelligence), in Support of Defense Suppression. UCAVs are planned to conduct a pre-emptive attack on integrated air-defense systems, operating from ordinary airfields and flying ahead of the

manned strike package, then continuing to provide reactive suppression. Once this initial SEAD task has been completed, the UCAVs could switch to strikes against well protected high-value targets (DSB, 2004).

2. Technological Aspects of UCAVs

A statement of USAF Air Combat Command summarizes the main aspect by noting that, "Removing the pilot from the vehicle opens up the design space and provides the catalyst for exploring clean sheet of paper system design philosophies and concepts of operations." (Hewish, 1999).

This means that the ability to remove one of the most technology-intensive and cost demanding factors from an aircraft design (i.e., the pilot) offers new ways to introduce revolutionary designs, capabilities, and concepts. These include combinations of the following:

- High-altitude flight capabilities and the ability to loiter for several days make UCAVs virtually immune for attacks by surface-to-air missiles or fighter aircraft.
- Small airframe designs with low signatures and enhanced stealth properties can penetrate enemy airspace without detection.
- UCAV designs comprise new, unconventional approaches for start and recovery, which might have influence on strategic considerations (SAB, 1996).
- Quality and safety standards are not necessarily as high as for manned aircrafts. Test and Evaluation can be abbreviated to lower development costs. Commercial Off the Shelf (COTS) products can find their way into military aviation.
- Cost of ownership is predicted to be 50-80% lower than manned systems, which results from the adoption of condition-based maintenance, minimized use of onboard sensors, a reduction in fluid-based systems, and a modular avionics architecture. Without the training needs for pilots and simulation training for the controllers, UCAV flight hours can be restricted to test and evaluation flights. Operator training can be conducted in simulators, which largely reduces training costs. (Sweetman, 2002).

- Enhanced Automatic Target Acquisition (ATA) and Automatic Target Recognition (ATR) capabilities. ATA and ATR allow a weapon to acquire targets of opportunity based on parameters programmed into its memory. Eventually, automatic vehicle identification, faster and better than human capabilities, will be possible. But despite all advances, developers today are aware that “before robotic weapons start winning wars, they will have to win the battle against ‘signal-to-noise'” (Beal, 2000).

Currently, ongoing research and development is underway to integrate autonomous detection, tracking, target recognition, and attack-coordination functionalities. The following overview concentrates on the current development of concepts for the employment of autonomous attack UCAVs for SEAD, TBMD, and CWMD.

3. Current and Projected UCAV Designs

There are two competing strategies that repeatedly show up in all these concepts and implementations. The key to these different approaches is the process of target detection, tracking, and recognition as well as the attack decision.

The first strategy places smart weapons on “dumb” launchers or air vehicles, which means the transport vehicle has the sole task of starting or transporting the intelligent fire-and-forget weapon to the target area. The intelligent weapon is equipped with ATD/ATR functionalities and is capable of attacking the target autonomously. The transport, as well as the weapon, can be a UAV/UCAV, but this description also includes munitions released by manned aircraft and artillery-launched smart munitions.

a. Autonomous Munitions with ATD and ATR

The main advantages of this configuration are:

- Fire-and-forget capability and a higher stand-off range. External target designation and target illumination are not necessary because the ATD/ATR capabilities of the munitions. Therefore, the transport platform can have a lower signature and consequently less vulnerability.

- Flexibility of attack strategies because simultaneous attacks are not limited by constraints of the targeting device.
- Redundancy of the detection and attack functionalities. There is no single point of failure for the targeting and classification mechanism (compared to a targeting device that is guiding several munitions). Every single munition contains all necessary functionalities.

These properties are realized at the expense of:

- Expensive targeting and processing hardware that is destroyed with the weapon, which leads to higher recurring costs.
- Attack coordination that is harder to implement due to necessary many-on-many coordination and communication. If coordination is not implemented, reduced effectiveness in swarm tactics due to multi-targeting and operational constraints (flight level management) can be expected.
- Lower maintenance and upgrade costs. More expensive hardware upgrades of ATD/ATR elements due to higher numbers of munitions compared to transport systems.

The following examples show current realizations of the above configuration. Israel Aircraft Industries builds the ground-launched Harpy drone, which carries a passive radiation-homing seeker and a fragmentation warhead. It is truck-launched and loiters in the area of a target for extended periods. To extend the engagement possibilities, IAI and Raytheon Missile Systems intend to produce Cutlass, the Combat UAV Target Locate and Strike System. It refits the Harpy air vehicle with a guidance system based on Raytheon's seekers for the AIM-9X (Sidewinder) and ASRAAM air-to-air missiles coupled with an automatic target-recognition and classification system. (Hewish, 1999).

As mentioned in the Introduction, the distinction between small UCAVs and intelligent submunitions is quite subjective (Hewish, 2002). A number of these weapons are currently competing with semi-active guided weapons for a place in the Small-Diameter-Bomb-Rack (SDB) of the Joint Strike Fighter (JSF) (Sweetman, 2002). The primary intent is to allow the JSF a higher stand-off range and less time over the tar-

get area without loss of effectiveness and precision. The same technology is also projected to equip larger, longer endurance UAVs with PGM without major changes in the targeting system.

One of these intelligent submunitions is the Brilliant Anti-Armor Submunition (BAT), which is usually dispensed by Army Tactical Missile System (ATACMS) and glides deep behind enemy lines. The target acquisition and attack decision is based on a target database and a target acquisition algorithm. In the future, BAT will be able to tell the difference between tracked and wheeled armor and perhaps between friendly and hostile platforms based on the silhouette of the vehicle (Beal, 2000). Another candidate for a place in the SDB rack is Lockheed Martin's mini-UCAV with integrated warhead, the Low Cost Autonomous Attack System (LOCAAS) (Defense Daily, 2004, November; Jane's, 2004, October). It is a loitering intelligent munition that comes in versions with and without turbojet propulsion. The propulsion provides loitering up to thirty minutes and ranges up to 100 kilometers at a speed between 200 and 300 knots. The loitering altitude is between 300 to 2000 feet. It is designed to be launched by aircraft, UAV, missile or directly from a ground-based starter. LOCAAS is equipped with a Laser Detection and Ranging seeker (LADAR), inertial navigation system (INS) and target recognition programs. The primary technical challenge the program currently faces is ATA and ATR. These functions will be critical for the weapon to differentiate between different target types and decoys, communicate with other LOCAAS, and then conduct strikes. In field tests, LOCAAS demonstrated a "near-zero" circular error probability (CEP) and the small size and precision of LOCAAS is designed to automatically limit the chance of collateral damage (Jane's, 2004). Modifications have been applied, including GPS, range extension, seeker improvements, and anti-jam capabilities. LOCAAS search algorithms will be based on genetic concepts that evolve using a trial-and-error approach that allows the microprocessor to remember conditions and create a hierarchy for processing events. Despite all advances, there are still concerns about the reliability of the performance in real-world combat conditions which will most likely lead to a semiautonomous engagement mode initially. If equipped with data links, LOCAAS weapons could fly in an attack swarm using "wolf pack" tactics to identify and attack targets together. These capabilities would enable the UCAVs to establish engagement coordination by broadcasting targeting

information. In 2002, the US Naval Surface Warfare Center Dahlgren Division (NSWCDD) submitted a proposal for a three year advanced concept technology demonstration (ACTD) of the Vertical Launch Autonomous Attack System (VLAAS) proposed by Lockheed Martin. This consists of a modified Vertical Launch anti-submarine rocket (ASROC-VLA) round carrying four to six units of the LOCAAS in place of the normal Mk46 torpedo (Lopez & Sirak, 2002; Jane's, 2002).

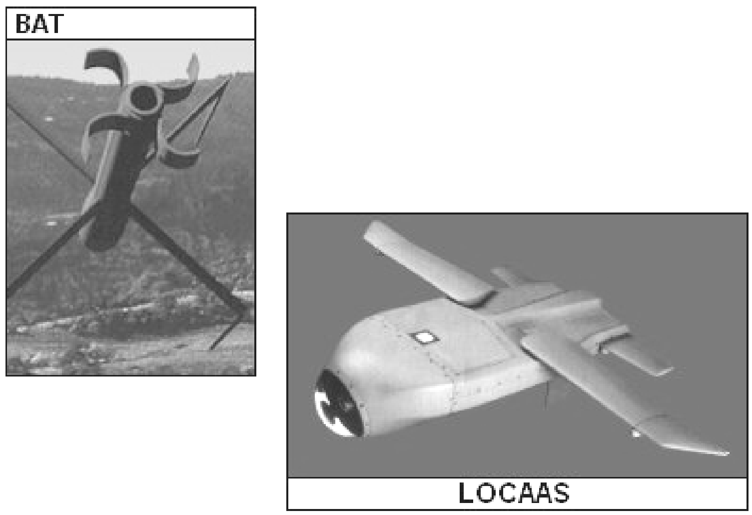

Figure 1 Left: Brilliant's BAT; Right: Lockheed Martin's LOCAAS

One of the munitions for the Army's new Non-Line-of-Sight Launch System (NLOS-LS) is the Loitering Attack Missile (LAM), developed by Lockheed Martin and Raytheon and based on LOCAAS technology (Space Daily, 2005). It is ground launched, carries a LADAR seeker for large area search capability, a turbojet motor, and wings that extend on launch. The missile has a 70-kilometer range with a 30-minute loiter time and 45 minute cruise with micro turbojet engine. It can loiter over targets of interest, conduct ATR and attack targets on its own. LAM provides network capability and maneuver/control elements for redirect, target acquisition, and downlinked images (Haynes & Hyman, 2004).

Another kind of loitering munitions are special artillery munitions. The technology and the area of application are similar to the previously-described UCAVs. These munitions are released over the target area and detect, classify and attack targets

autonomously. The difference is the limited search area, approximately 200 meters in diameter, due to descent by parachute instead of a gliding or propelled phase. An example of such a weapon is the German SMArt-155mm munition developed by the companies Diehl and Rheinmetall. It is equipped with a multimode seeker featuring an IR sensor, microwave radar, and microwave radiometer. Flight characteristics are defined by fins and a braking parachute. It contains an explosively-formed kinetic energy penetrating warhead (Inabnit, 2002).

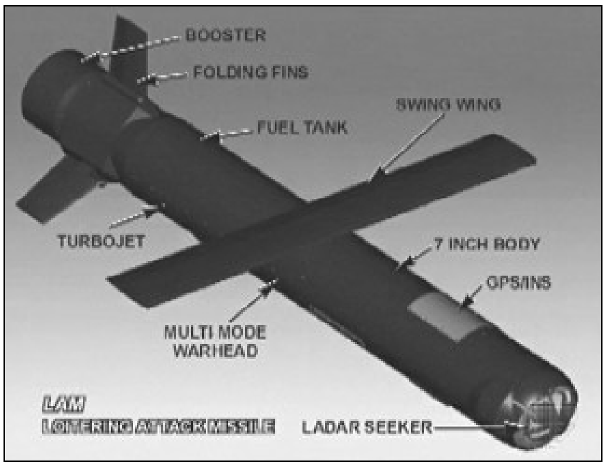

Figure 2 Left: Lockheed Martin’s LAM; Right: Rheinmetall’s SMart 155

b. Autonomous UCAVs using Munitions without ATD/ATR

The second strategy places dumb weapons on smart UCAVs. Here, the weapon is simply a guided or self-guided weapon without target recognition and attack decision. The advantage of this strategy is that the smart platform is recoverable. Especially for complex ATD/ATR-systems this approach is more cost effective. Advantages in particular are:

- Recurring ammunition unit costs are lower. Expensive ATR hardware can be reused. Upgrades of ATD/ATR hardware are less costly because only the targeting platforms, rather than every munition, needs to be upgraded.
- Easier attack cooperation. No communication capabilities are needed for coordination when the munitions are launched or managed from a single targeting platform.

- Easier to control and coordinate if man-in-the-loop is a required rule of engagement (ROE).

These advantages come at the cost of:

- Dependency of all submunitions on the targeting platform. This represents a single point of failure for the complete system and limited attack capabilities (response time and simultaneous engagement) by the targeting mechanism.
- Munitions are not necessarily fire-and-forget weapons. This results in enhanced vulnerability of the targeting platform and emission control (EMCON) issues.
- More sophisticated ATD/ATR systems are necessary for the required greater stand-off distance needed for maintaining higher survivability.

The following examples show current realizations of this concept. Current UCAVs using munitions without ATR are Boeing X-45A and Predator equipped with Hellfire missiles. There are a number of current acquisition programs to equip larger UCAVs with weapon modules (that are based on the SDB-rack) for a variety of tasks (Fulghum, 2002). These developments are still preferred over the autonomous munitions due to the prevailing USAF policy of man-in-the-loop (Sweetman, 2004). Engagements with only few targeting platforms, or forward-observer ground-based targeting and autonomy as a fallback option, are still easier to control and are more accepted by public opinion (Sirak, 2004).

Figure 3 Boeing's X-45A

In the early 1990s, the US Ballistic Missile Defense Organization (BMDO) proposed a boost-phase intercept (BPI) program that intended a long-endurance, high-altitude UAV RAPTOR (Responsive Aircraft Program for Theater Operations) to launch a high-velocity missile designated TALON (Theater Application Launch On Notice). The missile was planned to engage at a speed of approximately 3.3km/sec and a range of 50-220km. The RAPTOR was designed to stay aloft for two days at a height of 65,000ft and carry two TALONS and the on-board sensors necessary for a BPI engagement. This concept was designed to permit engagement of a Scud from a stand-off distance of about 100km, or the Chinese CSS-2 from 220km (BMDO, 1994).

4. UCAV Engagements

This section introduces several engagement scenarios and tactics for UCAVs that are proposed in military studies (SAB, 1996; DAB, 2004).

The first scenario is TBMD where UCAVs launch a counterattack on mobile, ballistic missile launching platforms following their attack. The success of the counterattack depends on the ability of the UCAVs to engage the launchers before they are camouflaged, sheltered or reloaded for another attack. This time period is expected to be about ten minutes (Fulghum & Wall, 2000). During this time, the UCAVs must be transported to the target area by a hypersonic missile which carries four to twelve UCAVs as payload. In addition, the trajectories of the ballistic missiles must be analyzed, the launcher positions must be extrapolated, and the counterattack must be approved. Above the target area, the missile decelerates to subsonic speed and releases the payload. The UCAVs start immediately and autonomously the loitering and target acquisition phase with the objective to engage and kill the missile launchers. Due to the relatively precise target position information in this case, the average time to detect and engage the targets is relatively short.

These tactics can also be applied for the stand-off engagement of targets with less precise target position information. SEAD missions, as well as CWMD missions, can be conducted by using fast transport vehicles to bring WASM, like LOCAAS, to the target

area. These munitions are equipped with extended loitering and ATD/ATR capabilities and can effectively fight targets which are distributed over larger areas.

Other engagement strategies of small UCAVs exploit their relative low cost for exhausting enemy resources and revealing enemy air defense locations. A single UCAV costs approximately $40k while surface to air missiles (SAM) cost approximately $100k. Therefore, unless the attacked target is defended by an inexpensive and effective point-defense weapon such as PHALANX, the exchange ratio is in favor of the UCAVs (Mirkarimi & Pericak, 2003).

For intercepting ballistic missiles in the boost phase (BFI), a UCAV at an elevation of more than 65,000ft could launch a high-velocity missile equipped with an infrared seeker, and a kinetic kill vehicle (KKV) (DSB, 1996). The UCAV would benefit from the high altitude by being less vulnerable to surface-to-air missile systems, by the enhanced detection radius, and by a larger time window for the engagement. The KKV is expected to intercept its target at an altitude of 65,000-260,000ft, 25-150km from the launch position, with a total elapsed mission time of 20 to 60 seconds. Variants of the weapon would also be suitable for engaging cruise missiles, other UAVs, manned aircraft, and surface-based targets such as TBM launchers and WMD production and storage facilities (BMDO, 1994). For these purposes, it is necessary to design a long-endurance UAV platform with ATD/ATR for boost-phase intercept (BPI) of tactical ballistic missiles.

The US Defense Advanced Research Projects Agency (DARPA) has examined armed UAVs as part of its Low Cost Cruise Missile Defense program. It planned to use a recoverable drone, equipped with inexpensive fire-control sensors and armament, to facilitate a semi-autonomous engagement of cruise missiles at long range. The drone is initially ground based and controlled until it reaches the target area where it loiters independently. It detects, classifies and attacks cruise missiles autonomously or semi-autonomously with air-to-air missiles.

B. THE MODEL AND PREVIOUS WORK

1. Modeling Requirements

The mathematical models that represent the deployment and operation of autonomous UCAVs have to capture the key aspects of their engagement process. Tradeoffs among sensing, data processing capabilities, lethality, and vulnerability have to be explicitly represented in the model for the analysis of the employment process in different scenarios and under different design considerations. There are four factors that negatively affect the performance of a swarm of autonomous UCAVs: (i) multiple kill due to simultaneous targeting and attack of a single target by several UCAVs, (ii) multiple kill due to misclassification of killed targets (imperfect BDA), (iii) ineffective engagements (misses), and (iv) UCAV attrition due to technical failure or interception. To address and analyse these factors with respect to the design and scenario parameters, the model must include the following analytical capabilities.

(i) Effects of multi-kill in swarm attack tactics: The mathematical model has to include methods to describe the effects of multi-kill due to simultaneous targeting (multiple acquisition) and imperfect BDA. The model must be able to explore the dependency of design and scenario parameters on each cause of multi-kill.

(ii) The effect of coordination in swarm attack tactics: The mathematical model must represent the possible exchange of targeting information among UCAVs and evaluate its effect on the outcome of the engagement.

(iii) Influence of a specific UCAV design parameter: The mathematical model must reflect influences of technical and operational parameters (detection rate, sensitivity and specificity of the sensors, attack rate, UCAV's failure rate, kill probability and level of coordination among UCAVs) on the MOEs.

2. Modeling Approach and Previous Work

Extensive work has been done in the areas of general search and detection, classification, and identification. However, analytical work on the whole engagement process of UCAVs, including attacks, is mostly restricted to a single or a small number of

UCAVs, or assumes centralized control (Decker, 2004). Most of the research on swarm tactics with simultaneous engagement is in the form of simulation models. A popular model approach is discrete event simulation with simulation APIs, such as the SIMKIT Discrete Even Simulation (DES) (Buss, 2005).

The detection process is described in the literature in several variations. Most classic works concentrate on the probability of detecting one or a number of targets in a specific area and on the optimization of some search criteria (Koopman, 1980; Stone, 1975; Washburn, 1980). Richardson, Stone and Washburn wrote surveys on moving target search problems (Richardson, 1986; Stone & Washburn, 1991). The detection and engagement process with imperfect BDA, in the form of Markov models, has been addressed by Gofer and Kress and explored the impact of imperfect BDA and memory on the engagement process of UCAVs with a single warhead (Gofer, 2003). Decker, extending previous works by Jaques and Pachter, modeled an engagement process for a multi-warhead UCAV on stationary targets with imperfect BDA for different search scenarios (Decker, 2004; Jaques & Pachter, 2002).

The simultaneous engagement process is splits into six functional components. This split is intended to simplify the construction of the complete model by addressing each functional component of the engagement process separately. This modular approach also facilitates extensions and modifications of the basic model.

a. Search and Detection Process and Attack Mechanism

Two main factors affect the search and detection component: (i) Detection rate and (ii) Detection range. While the detection rate affects the loitering time, the detection range is necessary for calculating the attack time. We make the following assumptions for the search and detection process.

- Targets form a Poisson Field (Jaques & Pachter, 2003; Decker, 2004). Targets move randomly in the target area, such that at any time they are spatially distributed according to a spatial Poisson distribution. A similar assumption for stationary targets is made by Decker and Gofer (Decker, 2004; Gofer, 2003).

- Repeated, random, independent, and memory-less search. UCAVs search autonomously in a random search pattern. A UCAV has no memory of its previous detections or detections of other UCAVs. Therefore, a target (real or false) can be detected multiple times. This assumption is necessary to model a moving target detection problem without implementing a complex tracking algorithm. Reinvestigating a location that earlier contained a false target might lead to a target detection due to target movements.
- Interrupted search and infinite search capability. Following a detection, the target is classified instantaneously as a real or false target. If it is classified as false target, a new search process is started in which the UCAV might detect the same target again (due to the aforementioned lack of memory). The search process is not limited by the endurance of the UCAV.

Under these assumptions, the detection process is a Poisson Process and the time to the next detection is an exponentially distributed random variable. Note that the rate of this process is an aggregated parameter that depends on a variety of different factors, such as UCAV capabilities and scenario properties. If the detection rates for targets, destroyed targets, and false targets vary due to different signatures, the detection processes have to be implemented with target type and status-dependent detection rates.

This model assumes that the sensors detect a target with a certain, range-dependent, probability. It also assumes that the detection probability is monotone decreasing with distance to the target. That means that a suitable rough approximation for the detection range is an exponential distribution truncated by the finite maximum detection range. Similar detection estimates with exponential detection functions are also used by Iida and Koopman as consideration of search effort and detection success (Iida et al., 2002).

The attack mechanism depends on weapon characteristics and the results of the detection process. Weapon characteristics comprise fire control and trajectories that affect the attack time, which is the parameter of interest for the simultaneous targeting (multiple acquisition) problem. The time it takes for the UCAVs to travel the detection range can be considered as attack duration if the classification time is negligible.

Consequently, for a constant attack speed, the attack duration has the same distribution as the detection range divided by the attack speed. Thus, to simplify the model, we assume that the attack duration is approximately an exponentially distributed random variable.

For model consistency, the considerations in the detection and attack component require that flight (loitering) altitudes for the search phase, in order to be neglected, be small compared to the detection ranges. This is necessary to provide independence of the detection frequency and the attack duration and allow use of the exponential distribution for the attack duration. If targets could be detected from high altitudes, the attack duration would be at least the time it takes the UCAV to hit the ground. This would not be displayed by the assumed exponential distribution.

b. Classification Process (BDA)

A detection of a target begins the classification process. Earlier research assumed a random time duration of the classification process (Stone & Stanshine, 1971). For modern and advanced UCAVs, the classification processing time is negligible compared to the search and attack durations. This work therefore assumes an instantaneous classification result. While some works (Decker, 2004) claim a dependency between the sensitivity (probability to accept real targets) and specificity (probability to reject false targets) of a sensor in analog systems, these parameters are considered to be independent in our model to account for capabilities of modern signal-processing systems and provide flexibility in the analysis. Our model considers destroyed targets as false targets and uses the same detection rate and classification parameters for destroyed targets and false targets. If the ATR results for destroyed targets and false-targets vary, ATR has to be implemented in the model with target-type and status-dependent detection rates and BDA parameters.

c. UCAV Attrition

The reliability of electronic components and mechanical parts is typically expressed in the literature by the exponentially distributed Time Between Failure (TBF). The same expression is adopted here for attrition caused by enemy area air defense in the

search and attack phase of the UCAV. Both components of attrition are expressed by an exponentially distributed time to failure (or removal) of an UCAV.

d. Weapon Effectiveness

The weapon effectiveness is represented by the frequently used Single Shot Kill Probability (SSKP). In this model it represents the probability for a kill if the UCAV reaches its target. The SSKP is an aggregated parameter for the UCAVs capability to (i) penetrate the target's close-in defense systems and (ii) the ability to achieve at least a mission-kill by hitting the target. This parameter is target-type dependent.

e. Attack Coordination Mechanism

We model targeting coordination to assess the benefit of avoiding multi-targeting situations. Due to the lack of previous work in this area, assumptions are based on capabilities of current UCAV-technologies. It is assumed that UCAVs are equipped with inexpensive cell phone technology, range-finding targeting devices, and GPS. This enables a UCAV to broadcast the target position it is about to attack as well as the attack duration. Each UCAV of the swarm keeps an attack list which leads to a rejection of a detected target included on that list. Imperfect coordination is implemented by the probability of correctly receiving a single attack message.

f. Model Composition

Since all time-related factors in our model (detection, attack, and attrition) are expressed as exponentially distributed random variables, it is possible to compose the model in the form of a continuous time Markov model with transient and absorbing states.

3. Measure of Effectiveness

The choice of Measures of Effectiveness (MOEs) depends on the context and objectives of the analysis and on the operational scenario. This section introduces possible MOEs applicable for analysis of tactical and design considerations of UCAVs.

a. Expected Relative Effectiveness (ERE-1)

An obvious MOE is the expected number of killed targets. However, to compare scenarios with different number of UCAVs, it may be more appropriate to replace this MOE with a relative measure. The ratio between the expected number of killed valuable targets and the initial number of valuable targets represents the relative effectiveness of the engagement.

$$\text{ERE-1} = \frac{\text{E [Number of Valuable Targets Killed]}}{\text{Initial Number of Valuable Targets}}$$

This MOE is useful for situations where no specific operational thresholds are applicable. Other applications include effectiveness studies of different weapon systems or tactics under controlled test conditions.

b. Expected Relative Efficiency (ERE-2)

The second MOE is the ratio between the expected number of killed valuable targets and the initial number of UCAVs. It is a measure of weapon's efficiency. This MOE shows the fraction of effective UCAVs and therefore also the fraction of ineffective, wasted UCAVs:

$$\text{ERE-2} = \frac{\text{E [Number of Valuable Targets Killed]}}{\text{Initial Number of UCAVs}}$$

c. Probability to Exceed an Operational Threshold (PET)

This MOE evaluates the mission success by the probability of exceeding a specific operational threshold in terms of number of kills. The operational threshold is a minimum fraction α of the number of valuable targets.

$$PET_{\alpha} = \Pr[\text{Number of valuable targets killed} \geq \alpha \cdot M] \quad 0 < \alpha \leq 1$$

where M = *Initial number of valuable targets*

This MOE is used for the evaluation and comparison of missions that have specific operational goals.

d. Number of UCAVs to Exceed an Operational Threshold (NET)

In the context of mission planning, it is of interest to calculate the number of UCAVs necessary to exceed an operational threshold with a certain probability χ. Specifically,

$$NET_{\alpha,\chi} = \text{Minimum number of UCAVs needed to obtain } PET_{\alpha} \geq \chi$$

One extreme application for this MOE is the requirement to kill all targets, $\alpha=1$, with a high probability, $\chi \in \{0.9,\ldots,0.99\}$. $NET_{\alpha,\chi}$ expresses the number of UCAVs necessary to accomplish a mission success. This MOE is applicable in particular when the mission is to engage critical targets.

e. Expected Duration of the Engagement

Time considerations always matter when UCAVs are employed to support operations in progress. This might be the case for the suppression of enemy air defense assets, an attack on supply systems, or the attack on well-protected units. In these cases, rapid engagement of enemy forces is an important criterion for the mission success. Therefore, for design and tactical considerations, the expected duration of the engagement might be an important factor for UCAV endurance and mission feasibility considerations.

4. Parameters

Due to the lack of unrestricted specification data and a wide variety of different UCAV and smart munition designs, a wide range of possible parameter-values must be considered. The values for detection, attack duration, and time to intercept/failure are especially likely to vary strongly between different scenarios. The parameters that describe the classification process and the warhead effectiveness, vary according to the UCAV-design, target signatures, and engagement tactics. Therefore, wide ranges of possible values must be considered for these parameters too. The parameters' base case and their ranges are introduced in the Chapter IV. These parameter values are obtained from an extensive literature review of unclassified data on current UCAV and Smart-Munition

designs, operational ideas and concepts and “educated guesses.” The objective is to demonstrate general issues of simultaneous multi-targeting in swarm tactics with a suitable implementation of a mathematical model.

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III. MODELS

A. GENERAL DESCRIPTION AND THE STATE SPACE

A UCAV can be in one of three possible stages: *search*, *attack* or *removed*. A UCAV is said to be in a *search* stage if it is loitering and it has not yet acquired a target. Once the UCAV detects a target, it instantly classifies it as valuable or non-valuable. If the detected target is classified (correctly or incorrectly) as non-valuable, the target is *rejected* (not acquired) and the UCAV moves on with its search. After a randomly distributed search time the UCAV detects another target. If the UCAV classifies a target as valuable, it enters the *attack* stage; it instantly acquires the target and then attacks it by flying directly at it. The randomly distributed attack time is measured from the moment the UCAV detects and acquires the target to the moment the UCAV hits the ground (or the target). Once a UCAV is in the attack stage, it is committed to attacking the acquired target and therefore cannot go back to the search stage, even if during the attack another UCAV hits the target and kills it. Thus, if several UCAVs acquire the same target, at most one of them can be effective. At the end of the attack stage the UCAV is destroyed and thus *removed* from further consideration. A UCAV can also be removed during the search and attack stages if it is intercepted by the enemy's air defense or crashes due to mechanical failure. We assume imperfect BDA (battle damage assessment); therefore classification may be subject to error. A valuable target may be classified as non-valuable and therefore passed over by the UCAV, and a non-valuable target may be classified as valuable and therefore attacked by the UCAV. We assume that the possible loitering time (e.g., due to fuel consumption) is long compared to the time it takes a UCAV to acquire and attack a target and the time it (possibly) crashes. In other words, a UCAV never runs out of fuel before its mission is over.

1. Notation

The probabilities of correctly identifying a valuable target and correctly identifying a non-valuable target are q_1 and q_2, respectively. That is, q_1 represents the *sensitivity* of the UCAV's sensors and data processing units, and q_2 their *specificity*. The acquisition attempts are independent. The sensitivity and specificity of the UCAV determine its *BDA*

capabilities. BDA (Battle Damage Assessment) refers to the ability of a shooter to distinguish between a live target, which is valuable, and a killed one, which becomes non-valuable. An acquired target is successfully hit and killed with probability *p*. We assume that the search time until detection and the attack time (time between detection and impact) are exponentially distributed random variables with parameters λ and μ, respectively. The mean detection time is a function of the size of the target area, its environment, sensor performance, target properties, loitering parameters (height, speed, search pattern) and weather. The mean attack duration depends on the detection range, attack speed loitering height and fire-control capabilities. During the search and attack stages, a UCAV may be removed due to enemy interception or mechanical failure. The time until (premature) removal has an exponential distribution with average $1/\varphi$. The launched pack comprises *N* UCAVs. The total number of targets (valuable and non-valuable) at the beginning of the operation in the target zone is *T*, out of which *M* targets are valuable and *T-M* targets are non-valuable.

Recall that each UCAV may be in one of three possible stages: *search*, *attack* and *removed.* A searching UCAV detects and instantaneously classifies a target after an exponentially distributed search time.

To summarize:

$$\begin{aligned}&\text{time to detect and classify a target is distributed as: } \exp(\lambda)\\&\text{attack phase duration is distributed as: } \exp(\mu)\\&\text{time to removal is distributed as: } \exp(\varphi)\end{aligned} \tag{3.1}$$

2. State Space Description

In order to model multi-attack and multi-kill events, a state in the Markov model must represent both the searching UCAVs and those which are in the attack stage following an acquisition. Moreover, the number of attacking UCAVs and the distribution of the attacking UCAVs on the targets have to be explicitly expressed too. In other words, the state space should be detailed enough to identify how many targets are attacked, and by how many UCAVs each is attacked simultaneously. Accordingly, the state description

consists of the number of UCAVs in search mode, *n*, and the number of targets attacked by *x* UCAVs, m_x, $x \in \{0,1,2,...N\}$. A state is described by the vector:

$$(n,\ \underbrace{m_0, \underbrace{m_1, m_2, ...m_x, ..., m_N}_{\text{attacked valuable targets}}}_{\text{total number of valuable targets}}\ )$$

$$\begin{aligned} n, x &\in \{0,1,...,N\} \\ m_0 &\in \{0, 1, 2, ...,M\} \\ m_x &\in \{0, 1, 2, ...\min(M, N/x)\}\ \forall\ x>0 \end{aligned} \tag{3.2}$$

Therefore, the state dimension is equal to the initial number of UCAVs, *N*, plus two.

An *absorbing state* in the engagement process is of the form $(0, m_0)$ or $(n, m_x = 0; x = 0,...N)$, which means that there are no UCAVs at the searching stage (*n* = 0) and no UCAVs at the attack stage $(m_x = 0; x = 1,..., N)$ or no valuable targets alive $(n, m_x = 0; x = 0,..., N)$. The number of valuable targets killed by the UCAVs in an absorbing state is $M - m_0$.

Example: let *M* = *N* = 2. There are 11 possible states: (2,2,0,0), (1,2,0,0), (1,1,1,0), (1,1,0,0), (0,2,0,0), (0,1,1,0), (0,1,0,1), (0,1,0,0), (0,0,2,0), (0,0,1,0) and (0,0,0,0). For example, the state (1,2,0,0) represents the situation where one UCAV is searching and the other UCAV is removed (acquired a non-valuable target or missed a valuable target or has crashed or has been intercepted). The state (1,1,0,0) represents the situation that the removed UCAV successfully acquired and killed a valuable target.

Due to the dependencies of *n* and m_x, expressed in (3.2), the following constraints apply for the state description:

$$
\begin{aligned}
& m_x \leq \min\left(M, \frac{N-n}{x}\right) \qquad \forall\, x > 0 \\
& \sum_{x=1}^{N-n} x \cdot m_x \leq N - n \qquad\qquad (3.3) \\
& \sum_{x=0}^{N-n} m_x = m
\end{aligned}
$$

Figure 4 and Figure 5 demonstrate the increasing number of states and state transitions with the initial number of UCAVs, *N*, and the initial number of valuable targets, *M*.

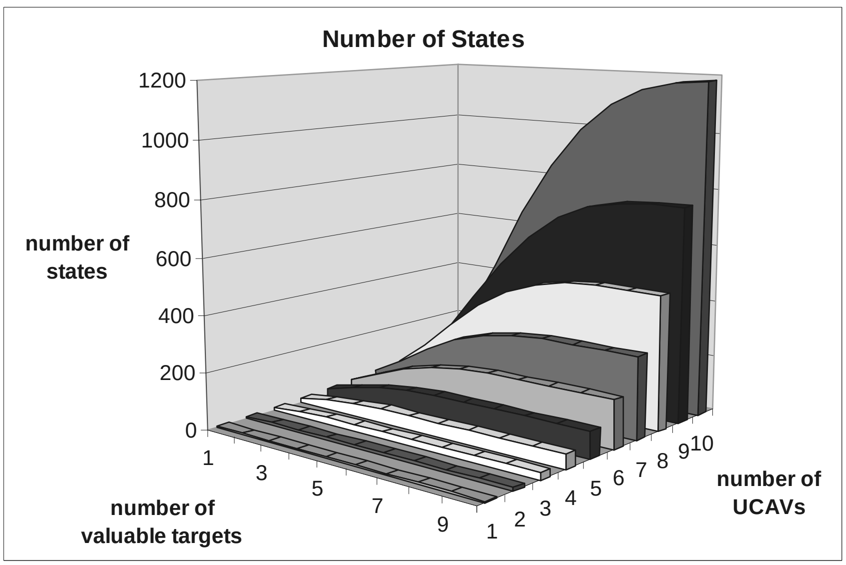

Figure 4 Number of States, UCAVs and Valuable Targets

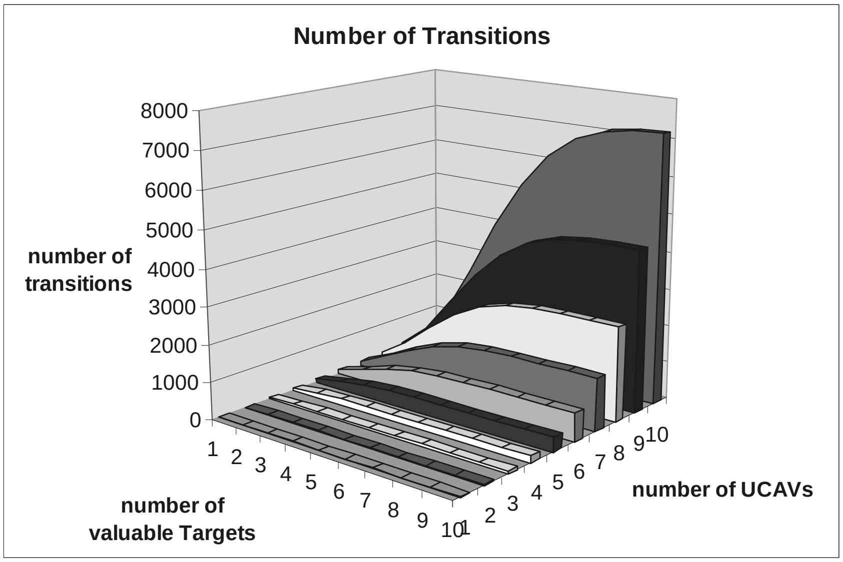

Figure 5 Number of State-Transitions, UCAVs and Valuable Targets

3. General Structure of the State Transition

To simplify the initial exposition, we start off with a basic model where we assume perfect BDA, meaning, detected valuable targets are always classified as such and attacked, while detected non-valuable targets are always classified as non valuable and rejected. Formally, $q_1=q_2=1$. A transition in the Markov model occurs when one of the following events happen:

a) Detection: a UCAV detects a target and examines it

b) Impact: a UCAV hits the ground following an attack

c) Removal: a UCAV is intercepted or experiencing a technical failure

The transition probabilities for detection, impact or removal are obtained as a race of exponentials. The probability that the next event is *detection* increases with the number of UCAVs in search mode, the number of targets in the area, and the reciprocal of the average time to detection ($1/\lambda$).

$$\frac{T \cdot \lambda \cdot n}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.4}$$

The probability that the next event is *removal of a UCAV* increases with the number of UCAVs in search and attack modes and the reciprocals of the average time to interception (*1/φ*).

$$\frac{\varphi \cdot \left(n + \sum_{i=1}^{N} m_i \cdot i \right)}{\left(T \cdot \lambda + \varphi\right) \cdot n + \left(\mu + \varphi\right) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.5}$$

The probability that the next event is be an *impact of an UCAV* increases with the number of UCAVs in attack mode and reciprocal with the average attack time (*1/μ*).

$$\frac{\mu \cdot \sum_{i=1}^{N} m_i \cdot i}{\left(T \cdot \lambda + \varphi\right) \cdot n + \left(\mu + \varphi\right) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.6}$$

4. Transition Probabilities under Different Assumptions

Different technical and tactical assumptions are implemented for the purpose of model development. As with all models, assumptions which might not hold may have to be changed. The use of this kind of models allows enough flexibility to deal with changes in technical and tactical evaluations. For example, one fundamental assumption is that the detection rates for valuable and non-valuable targets are the same. This assumption is accurate when the valuable and non-valuable targets (killed and dummy targets) look similar through the sensor's eyes. However, if the target changes its physical properties in a way that causes the detection signature for the UCAV's sensors to change (for example, a killed target is burning and the UCAV uses an infrared sensor) then the detection rates must reflect this situation. In this example, it might also be necessary to differentiate the detection rate for dummy targets due to the lack of movement or the like.

The developed state description allows tracking of the number of valuable targets, dummy targets, and killed targets by simple subtraction. Given that the detection fre-

quencies for valuable, killed, and dummy targets are λ_v , λ_w, *and* λ_d respectively, the probability of detecting a valuable target develops to:

$$\frac{n \cdot \lambda_v \cdot \sum_{i=0}^{N} m_i}{\left(\underbrace{\lambda_v \cdot \sum_{i=0}^{N} m_i}_{\text{val.targets}} + \underbrace{\lambda_d \cdot (T - M)}_{\text{dummy targets}} + \lambda_w \cdot \underbrace{\left(M - \sum_{i=0}^{N} m_i \right)}_{\text{killed targets}} + \varphi \right) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i}$$

with the total number of targets, *T*, and the initial number of valuable targets, *M*.

This example illustrates how refinements can be applied to other parameters without major changes in the model itself.

B. THE BASIC TRANSITION MODEL

The assumption of perfect BDA implies that only valuable targets are attacked. Non-valuable targets, and in particular killed targets, are always identified as non-valuable and therefore rejected. However, incidents of multiple kills can occur even with perfect BDA, when more than one UCAV acquires the same target. If at least one UCAV is attacking, the race of exponentials among the searching UCAVs, the attacking UCAVs and the removal process determines whether the next state transition is an acquisition of a target, an impact of a UCAV or a removal (interception or failure). With the conditional probability *p*, the attacking UCAV kills the target on impact, and with probability *(1-p)* the UCAV impacts and fails to destroy the target.

Modeling the influence of multi-kill events as a result of multiple acquisition requires differentiating a situation where a target is attacked by a single UCAV from a situation of multiple simultaneous attacks. Clearly, if a target is killed by a certain UCAV, all other UCAVs that are attacking that target are redundant. Therefore, equations (3.4) - (3.6) have to be modified to account for the situation of a number of simultaneous attacks on a particular target.

The following transitions are possible from state $(n, m_0, m_1, \ldots. m_n)$ in this scenario:

(i) A searching UCAV has detected a valuable target already under attack by $(x-1)$ UCAVs, classifies it correctly and attacks it. The probability is calculated by a race of exponentials where one of the m_{x-1} targets that are currently attacked by $(x-1)$ UCAVs wins.

$$(n, m_0, m_1, \ldots. m_n) \Rightarrow (n-1, \ldots, m_{x-1} - 1, m_x + 1, \ldots, m_n)$$

$\forall \quad x \in \{1,2,\ldots,n\} \mid (m_{x-1} > 0) \wedge (n > 0)$ with probability

$$\frac{\lambda \cdot n \cdot m_{(x-1)}}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.7}$$

(ii) A searching UCAV detects a valuable target, correctly classifies it as non-valuable target and continues searching.

$$(n, m_0, m_1, \ldots. m_n) \Rightarrow (n, m_0, m_1, \ldots. m_n)$$

$\forall \quad (n > 0)$ with probability

$$\frac{\lambda \cdot n \cdot \left(T - \sum_{i=0}^{N} m_i\right)}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.8}$$

(iii) An UCAV impacts on a valuable target under attack by x other UCAVs and kills it. The transition is expressed by removing the x-times attacked target. All UCAVs which attacked this target are automatically removed with the target:

$$(n, m_0, m_1, \ldots. m_n) \Rightarrow (n, \ldots, m_x - 1, \ldots) \quad \text{with } x = \{1,2,\ldots n\}$$

$\forall \quad x \in \{1,2,\ldots,n\} \mid (m_x > 0)$ with probability

$$\underbrace{\frac{\mu \cdot m_x \cdot x}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i}}_{\substack{\text{race of exponentials favoring an impact} \\ \text{on an x-times attacked valuable target}}} \cdot p \tag{3.9}$$

(iv) The state transition shown below can result from two events: (1) ineffective impact on a target, which is currently attacked (acquired) by *x* UCAVs and (2) removal of an attacking UCAV that attacks a target, which is currently attacked (acquired) by *x* UCAVs.

$(n, m_0, m_1, \ldots.\ m_n) \quad \Rightarrow \quad (n, \ldots, m_{x-1} + 1, m_x - 1, \ldots.) \quad \text{with } x \in \{1,2,\ldots,n\}$

$\forall \quad x \in \{1,2,\ldots,n\} \mid (m_x > 0)$ *Ineffective Impact on a Target*

$\forall \quad x \in \{1,2,\ldots,n\} \mid (n > 0)$ *Interception in attack mode*

with the transition probability for *Ineffective Impact:*

$$\frac{\mu \cdot m_x \cdot x \cdot (1 - p)}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.10}$$

and the transition probability for *Interception in attack mode:*

$$\frac{\varphi \cdot (m_x \cdot x)}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.11}$$

The overall transition probability is the sum of the transition probabilities of the two events.

(v) A searching UCAV is intercepted:

$(n, m_0, m_1, \ldots. m_n) \Rightarrow (n\text{-}1\ m_0, m_1, \ldots. m_n)$

$\forall\ (n > 0)$ with probability

$$\frac{\varphi \cdot n}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.12}$$

C. IMPERFECT BDA

The UCAVs must classify detected targets in order to start their attacks. If BDA is not perfect, this classification may be erroneous. Detected valuable targets can be classified as non-valuable and rejected, and non-valuable targets can be classified as valuable and therefore attacked. The degree of BDA depends on the UCAV's sensor performance and classification capabilities, on environmental factors and on enemy tactics.

The following model is an extension of the basic model and implements limited BDA properties. The limited classification BDA is expressed by the UCAV's capability to i) correctly classify a valuable target with the probability q_1, and ii) correctly classify a non-valuable target with the probability q_2.

The consideration of these probabilities, which influence the accept/reject decision (where accept=attack) leads to new transition events. A detected valuable target might be rejected and a detected non-valuable target might be attacked. The attack on a non-valuable target is expressed by the transition:

$(n, m_0, m_1, \ldots. m_n) \Rightarrow (n\text{-}1, m_0, m_1, \ldots m_n) \qquad \forall\ (n > 0)$

It has the same state transition formulation as an interception of an UCAV. However, the transition probabilities must be recalculated.

(i) The probability of an attack on a valuable target that is under attack by *(x-1)* UCAVs is :

$$\frac{1 \cdot \lambda \cdot n \cdot m_{(x-1)} \cdot q_1}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.13}$$

This transition probability is a generalization of the probability in (0.8)

(ii) The probability that a UCAV detects and attacks a non-valuable target is:

$$\frac{\lambda \cdot n \cdot \left(T - \sum_{i=0}^{N} m_i\right) \cdot \left(1 - q_2\right)}{\left(T \cdot \lambda + \varphi\right) \cdot n + \left(\mu + \varphi\right) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.14}$$

(iii) A detected valuable target is rejected if the UCAVs erroneously classifies it as non-valuable, and a non-valuable target is rejected if it is classified correctly. Thus, the rejection probability incorporates both the sensitivity of the UCAV and its specificity and is given by:

$$\underbrace{\frac{\lambda \cdot n}{\left(T \cdot \lambda + \varphi\right) \cdot n + \left(\mu + \varphi\right) \cdot \sum_{i=1}^{N} m_i \cdot i}}_{\text{Target Detection}} \cdot \left(\underbrace{\left(T - \sum_{i=0}^{N} m_i\right) \cdot q_2}_{\substack{\text{correct rejection} \\ \text{of a non-valuable target}}} + \underbrace{\sum_{i=0}^{N} m_i (1 - q_1)}_{\substack{\text{incorrect rejection} \\ \text{of a valuable target}}} \right)$$

$$\Rightarrow \qquad \frac{\lambda \cdot n \cdot \left(T \cdot q_2 + \sum_{i=0}^{N} m_i \cdot \left(1 - q_1 - q_2\right)\right)}{\left(T \cdot \lambda + \varphi\right) \cdot n + \left(\mu + \varphi\right) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.15}$$

The state-transition probabilities remain unchanged in all other cases, as expressed by (3.9) - (3.12) of the basic model,

D. IMPERFECT COMMUNICATION AMONG UCAVS

Suppose that the UCAVs can broadcast targeting information to other UCAVs at the time of the acquisition. If another UCAV receives this information, it would refrain from acquiring this target and will continue its search. Thus, this broadcast provides a form of attack coordination. The signal that is sent out by the attacking UCAV, which

stays on during the entire duration of the attack, is received and processed correctly by any searching UCAV with a fixed probability r. The signals from the various attacking UCAVs are independent. Thus, a searching UCAV that detects a target currently engaged by x other UCAVs will not attack it with probability $1\text{-}(1\text{-}r)^x$. Perfect coordination, $r = 1$, implies that no events of multi-kill due to simultaneous engagements can occur, while for $r = 0$ no targeting information transfer exists.

To implement attack coordination, the state space must be able to describe how often a target has been reported as attacked. This is necessary for valuable as well as non-valuable targets. Recall that the state space description of the basic model only allows for tracking the valuable targets; there is no explicit representation for multiple acquisitions of non-valuable targets. Therefore, the effect of targeting coordination on the probability of simultaneous attacks on non-valuable targets is neglected. However, when the specificity is high (q_2 is close to 1) or the total number of targets is high compared to the number of UCAVs, this effect is negligible and the state space description of the basic model can be applied.

1. Transition Probabilities –The Approximate Case

The following model extends the above models by implementing possible attack coordination by imperfect transmission of targeting information. The state space description of the basic model is used for simplicity, with the limitations noted in the previous paragraph. Therefore, the model description is restricted to scenarios with high specificity, (q_2 close to 1). The incorporation of possible attack coordination into the model adds another rejection criterion; a target classified as valuable can now be rejected if it has been declared as being acquired by another UCAV and this message is received by other UCAVs. The transition probabilities change for the cases of:

(i) *Acquisition of a valuable target.* The acquisition probability of a valuable target extends formula (3.13) with the condition that an acquisition of an x-times simultaneously attacked target occurs only if all targeting transmissions have failed. In that case, the transition probability from

state $(n, m_0, m_1, …. m_n)$ to state $(n\text{-}1,…, m_{x\text{-}1} - 1, m_x + 1,…, m_n)$ is

$$\frac{\lambda \cdot n \cdot m_{(x-1)} \cdot q_1 \cdot (1-r)^{(x-1)}}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.16}$$

(ii) *Rejection of a target*. A target is passed over when it is classified as non-valuable, or if it is classified as valuable but at least one attack message by a UCAV is received. The probability for the rejection of a target is

$$\frac{\lambda \cdot n \cdot \left((T \cdot q_2) + \sum_{i=0}^{N} m_i \cdot \left(1 - (1-r)^i \cdot q_1 - q_2\right)\right)}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} m_i \cdot i} \tag{3.17}$$

All other transition probabilities remain the same as for the model extension with limited BDA properties.

2. Transition Probabilities: The Complete Case

a. *The State Description*

To describe also multiple acquisition of non-valuable targets, the state description of the basic model must be extended. To track attacks on non-valuable targets, the easiest implementation is to mirror the case of valuable targets, that is,

$$\textit{State Description:} \quad \Big(n,\ \underbrace{m_{v0}, \underbrace{m_{v1}, \ldots, m_{vx}, \ldots, m_{vN}}_{\textit{attacked valuable targets}}}_{\textit{total number of valuable targets}}, \underbrace{m_{w0}, \underbrace{m_{w1}, \ldots, m_{wx}, \ldots, m_{wN}}_{\textit{attacked non-valuable targets}}}_{\textit{total number of non-valuable targets}}\Big)$$

$$\begin{aligned} &n, x \in \{0, 1, 2, \ldots, N\} \\ &m_{vx} \in \{0, 1, 2, \ldots \min(M, N/x)\}\ \forall\ x>0 \\ &m_{wy} \in \{0, 1, 2, \ldots \min(M, N/x)\}\ \forall\ x>0 \\ &m_{v0}, m_{w0} \in \{0, \ldots, M\} \end{aligned} \tag{3.18}$$

Here, m_{vx} and m_{wx} denote the number of valuable targets and non-valuable targets that are simultaneously attacked by x UCAVs respectively.

b. *State Transitions*

Analogous to the case where multiple acquisitions are recorded only for valuable targets, the transitions for the complete case are:

$(n, m_{v,0}, ...m_{v,x}..., m_{v,N}, m_{w,0},... m_{w,x},..., m_{w,N})$:

(i) *Acquisition of a valuable target, that is simultaneously attacked by (x-1) UCAVs:*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n\text{-}1, m_{v,0}, ...m_{v,(x\text{-}1)}\text{-}1, m_{v,x}+1,..., m_{w,N})$ with probability

$$\frac{\lambda \cdot n \cdot m_{v,(x-1)} \cdot q_1 \cdot (1-r)^{(x-1)}}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} (m_{v,i} + m_{w,i}) \cdot i} \tag{3.19}$$

(ii) *Acquisition of a non-valuable target that is simultaneously attacked by (x-1) UCAVs:*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n\text{-}1, m_{v,0}, ...m_{w,(x\text{-}1)}\text{-}1,..., m_{w,x}+1,..., m_{w,N})$ with probability

$$\frac{\lambda \cdot n \cdot m_{w,(x-1)} \cdot (1-q_2) \cdot (1-r)^{(x-1)}}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} (m_{v,i} + m_{w,i}) \cdot i} \tag{3.20}$$

(iii) *Rejection of a target:*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n, m_{v,0},..., m_{w,N})$ with probability

$$\frac{\lambda \cdot n \cdot \sum_{i=0}^{N} \left(m_{w,i} \cdot q_2 + m_{v,i} \cdot (1-q_1)\right) \cdot \left(1-(1-r)^{(i-1)}\right)}{(T \cdot \lambda + \varphi) \cdot n + (\mu + \varphi) \cdot \sum_{i=1}^{N} (m_{v,i} + m_{w,i}) \cdot i} \tag{3.21}$$

(vi) *Interception of an UCAV in search mode:*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n\text{-}1, m_{v,0},..., m_{w,N})$ with probability

$$\frac{\varphi \cdot \sum_{i=1}^{N}\left(m_{v,i}+m_{w,i}\right)\cdot i}{\left(T\cdot\lambda+\varphi\right)\cdot n+\left(\mu+\varphi\right)\cdot\sum_{i=1}^{N}\left(m_{v,i}+m_{w,i}\right)\cdot i} \tag{3.22}$$

(vii) *Effective impact (kill) on a target, that is simultaneously attacked by x UCAVs:*

Note, that with the status change at impact, the other *x-1* attacking UCAVs attack a non-valuable target.

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n, m_{v,0}, ...m_{v,x}-1,..., m_{w,(x-1)}+1,..., m_{w,N})$ with probability

$$\frac{\mu \cdot m_{v,x}\cdot x\cdot p}{\left(T\cdot\lambda+\varphi\right)\cdot n+\left(\mu+\varphi\right)\cdot\sum_{i=1}^{N}\left(m_{v,i}+m_{w,i}\right)\cdot i} \tag{3.23}$$

(vi) *Interception of an UCAV in attack mode on a valuable target, that is simultaneously attacked by x UCAVs* and *Ineffective impact on a valuable target, that is simultaneously attacked by x UCAVs*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n, m_{v,0}, ... m_{v,(x-1)}+1, m_{v,x}-1,..., m_{w,N})$ with probability

$$\frac{m_{v,x}\cdot x\cdot\left(\varphi+\mu\cdot\left(1-p\right)\right)}{\left(T\cdot\lambda+\varphi\right)\cdot n+\left(\mu+\varphi\right)\cdot\sum_{i=1}^{N}\left(m_{v,i}+m_{w,i}\right)\cdot i} \tag{3.24}$$

(vii) *Interception of an UCAV in attack mode on a non-valuable target, that is simultaneously attacked by x UCAVs* and *Impact on a non-valuable target, that is simultaneously attacked by x UCAVs*

$(n, m_{v,0},..., m_{w,N}) \Rightarrow (n, m_{v,0}, ... m_{w,(x-1)}+1, m_{w,x}-1,..., m_{w,N})$ with probability

$$\frac{m_{w,x}\cdot x\cdot\left(\varphi+\mu\right)}{\left(T\cdot\lambda+\varphi\right)\cdot n+\left(\mu+\varphi\right)\cdot\sum_{i=1}^{N}\left(m_{v,i}+m_{w,i}\right)\cdot i}$$

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IV. ANALYTICAL DESIGN AND RESULTS

A. ANALYTICAL DESIGN

1. Implementation of the Mathematical Model

The mathematical (Markov) model is implemented in the Java programming language, in which an auto generation algorithm for state description, state space, state transition, and transition probabilities has been developed. The high memory demand for running the program is handled by the utilization of forward star data structures (Ahuja et al., 1993), which is necessary in order to manage large state descriptions and large state spaces that are typical to real-world scenarios.

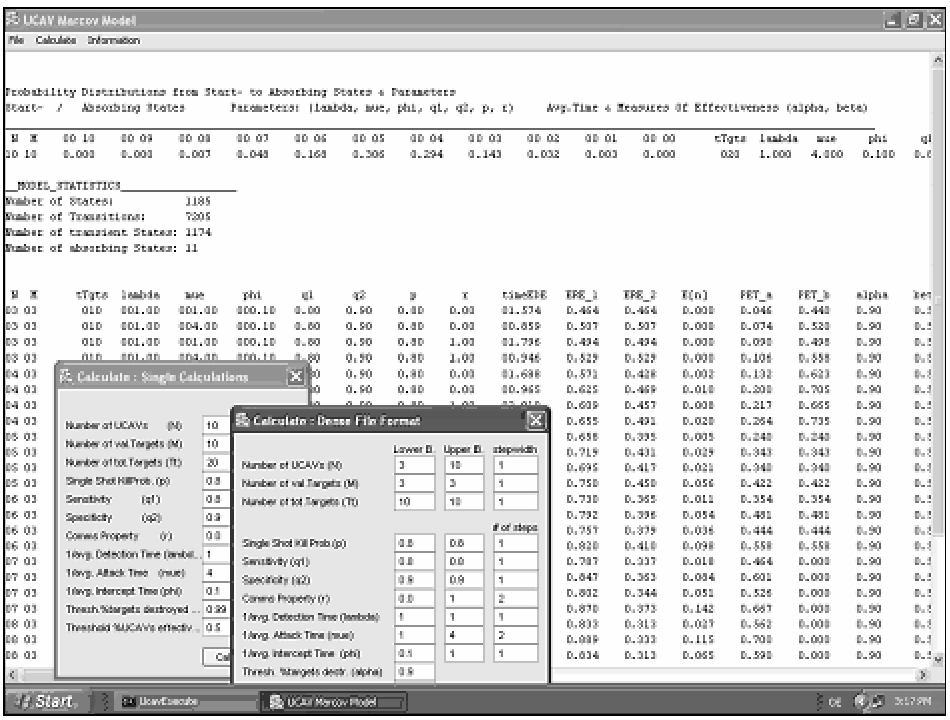

Figure 6 Screenshot of the Input/Output Window of the Java-Implementation of the Markov Model.

The model output is saved as text file and analyzed by MS EXCEL and the statistical package SPSS.

2. UCAV Design Points and Scenario Data

a. Categories of Parameters

The parameters of the model can be categorized in different ways. One way is to separate among design-related parameters, operational parameters, and scenario-related parameters. Since all of the parameters in this model, except *T*, are determined by factors of several different categories, a more relevant categorization of the parameters is into functional groups like detection, decision, survivability, and effectiveness.

b. Reasonable Ranges for Parameter Values

From the overview of UCAV technologies and doctrine in Chapter II, reasonable ranges for parameter values have been derived (see Table 1). Due to the restricted nature of original weapon specifications, the data used for this analysis is based on free available information and educated guesses. The high number of different UCAV designs as well as the large spectrum of operational tasks result in a large range of values for the parameters and the state variables (number of UCAVs, *N*, number of valuable targets, *M*, number of total targets, *T*).

Parameter	**Symbol**	**Low**	**ADP**	**High**
Classification Sensitivity	q_1	0.6	0.8	1.0
Classification Specificity	q_2	0.8	0.9	1.0
SSKP	p	0.6	0.8	1.0
Communication Capability	r	0	0	1
$\frac{\text{Avg. Time to Detection}}{\text{Avg. Attack Duration}}$	μ / λ	1	n.a.	40
$\frac{\text{Avg. Time to Detection}}{\text{Avg. Time to Attrition}}$	φ / λ	0	n.a.	1

Table 1. Parameter Values for the Analysis.
The Assumed Design Points (ADP) are used for the Sensitivity Analysis.

3. Analytical Approach

First the parameters p, q_1, q_2 are fixed at their assumed design point (ADP; see Table 1). We start off the analysis by varying the time related parameters λ, μ, and φ in scenarios with different numbers of UCAVs and false targets. Recall that in Chapter 3 we used the terms valuable targets and non-valuable targets. In the following, the term false targets is used for the initial number, (T-M), of non-valuable targets to emphasize impacts of starting conditions of the scenario. The term non-valuable targets is used for the sum of false targets and destroyed targets.

In the analysis, the term simultaneous multi-targeting (SMT) is frequently used to describe situations where a target that is currently under attack is detected (targeted) by other UCAVs. Depending on BDA, these detections can lead to simultaneous multi-attacks in cases without attack coordination. In cases of perfect attack coordination, SMT results in the certain rejection of a valuable target.

The first part of the analysis is done to identify at what values of the time-related parameter combinations does simultaneous multi-targeting (SMT) become an important influence factor. The results of this first step are used to identify two design points, one with strong and one with weak SMT impact. In a second step, sensitivity analysis with respect to p, q_1, q_2, and r at those two points is conducted.

The scope of this analysis is to provide insights into the dynamics of the combat situation and into the tradeoffs among some of the parameters (in particular, the effects of simultaneous multi-targeting). The analysis in this chapter is not intended to be exhaustive, but rather to demonstrate the capabilities of the model.

B. RESULTS

1. Identification of Multi-Targeting Situations

a. Effect of Detection, Attack, Attrition, and Coordination for Different Numbers of UCAVs

Figure 7 shows the impacts of detection rate, attack rate and attrition rate on the relative effectiveness of the engagement process. Recall that ERE-1 expresses the relative expected number of destroyed valuable targets. The time dependent parameters λ, μ, and φ are expressed as ratios, μ/λ and φ/λ, since the model depends on the ratios of these parameters and not necessarily on their absolute values. To demonstrate the impact of multi-kill due to SMT, we start off with a base case of four valuable targets and one false target, where p, q_1, q_2 are at their ADP. The term "comms" in Figure 7 indicates the cases with perfect communications, which also means perfect attack coordination (no simultaneous attacks on the same target occur).

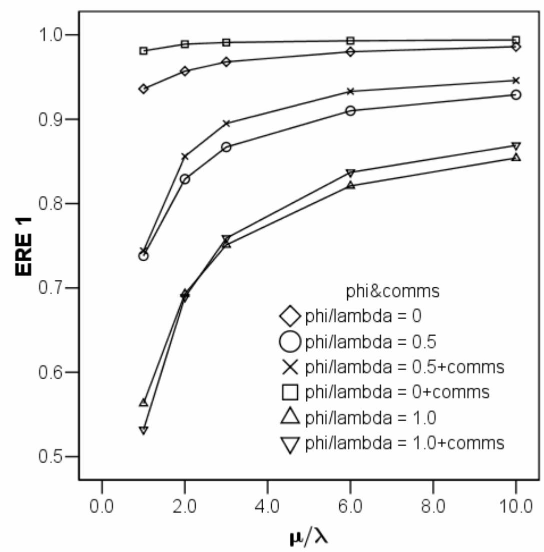

Figure 7 Influence of detection, attack, vulnerability, and coordination on ERE-1 (10 UCAVs, 4 valuable Targets, 5 total Targets, ADP)

Note that for small ratios (<4) of μ/λ ERE 1 is quite small. This observation is caused by different reasons. The main reason is the relative attrition with respect to

the detection rate (φ/λ). Recall that in our model the search and the attack phases have the same attrition rate φ .

Example: Assume a constant detection rate, λ, and a constant attrition rate, φ. Consequently the ratio φ/λ must be constant too. For small attack durations, most of the attrition events occur in the search phase. If the attack duration increases (decreasing μ/λ), more and more attrition events occur in the attack phase. This is observed in Figure 7 with the decrease of ERE-1 for $\varphi/\lambda=const$ and decreasing μ/λ. Therefore, the total attrition (search and attack phase) increases even if φ/λ is kept constant.

This effect is amplified by higher vulnerabilities, φ/λ. Recall that small ratios of μ/λ mean long attack durations compared to the detection times and greater φ/λ mean shorter times to UCAV removal compared to the detection times. For values of $\mu/\lambda > 4$, the impact of this ratio on ERE-1 is approximately linear up to $\mu/\lambda = 8$. Above this value, the dependency of ERE-1 on μ/λ is negligible for $\varphi/\lambda<0.5$. For the cases without attrition in Figure 7 the difference for ERE-1 with and without communication shows the impact of SMT. It is obvious that the effect of SMT is strong for values of $\mu/\lambda< 4$, weak for, $4 \le \mu / \lambda \le 8$, and not important for values above 8. Note that perfect attack coordination does not necessarily enhance the performance of the pack of UCAVs, as one would expect. For small values of μ/λ and high relative attrition rates $\varphi/\lambda=1$ the opposite is true; ERE-1 without coordination is in fact higher than with coordination. For low attrition rates and higher μ/λ, attack coordination enhances the performance of the pack. Thus, the influence of coordination through communication on the effectiveness of the attack depends on the combination of the time-dependent parameters.

Example for small μ/λ: Suppose a UCAV that rejects a valuable target because this target has been reported as being attacked. Before the UCAV can attack another valuable target, it is removed due to the high attrition rate. In the meantime, the reported attack on the valuable target fails.

Further note that for large values of μ/λ and the case of no attrition ($\varphi/\lambda=0$), the gap between the coordination and no-coordination cases decreases with in-

creasing μ/λ. This can be explained by the decreasing occurrence of SMT with increasing μ/λ and hence decreasing advantage benefits of coordination.

We will now examine if this observations are valid for other combinations of *N*, *M*, and *T*. Figure 8 shows the influence of different numbers of attacking UCAVs on the expected relative efficiency with and without communications.

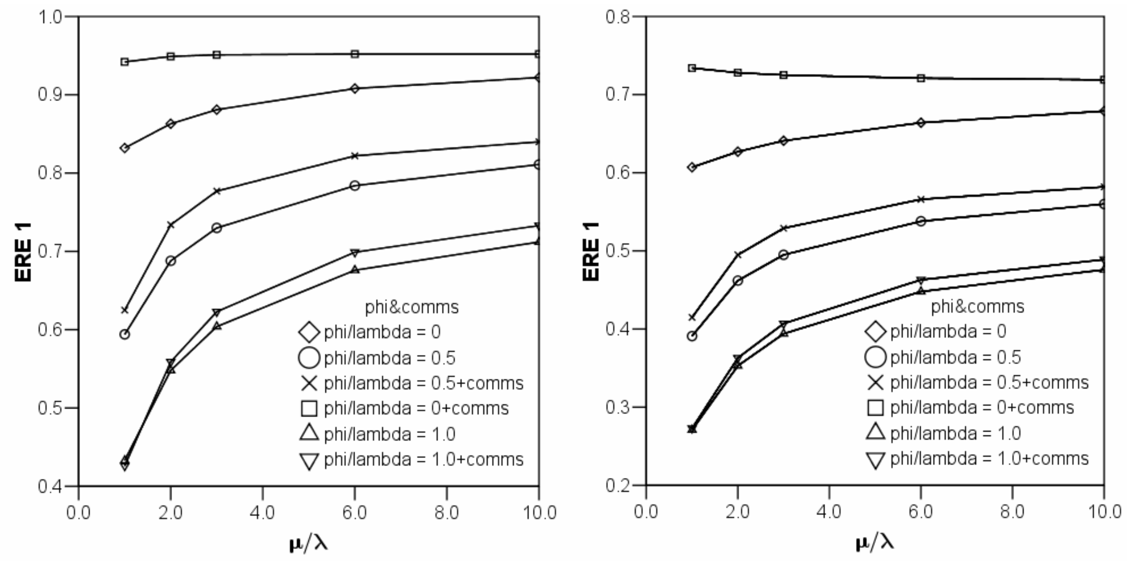

Figure 8 Influence of detection, attack, vulnerability, and coordination on ERE 1:
Left: 7 UCAVs, 4 valuable targets, total of 5 targets, ADP
Right: 4 UCAVs, 4 valuable targets, total of 5 targets, ADP

The results with four and seven UCAVs confirm the initial observations. Note that with smaller numbers of UCAVs the presence of attack coordination is more effective for higher attrition (larger φ/λ value) and longer attack durations (smaller μ/λ).

In the case of four targets, small μ/λ value and no attrition ($\varphi/\lambda=0$), an increase of ERE-1 is observed. This is a result of the small number of initial false targets (T-$M=1$). Here, attack coordination leads to SMT-free target allocation without great danger of misclassification. If the attack duration is shorter, the probability to detect a non-valuable target increases because, after the first attacks, destroyed targets add to the false targets.

b. Influences of Detection, Attrition, and Coordination for Different Numbers of False Targets

We continue with the exploration of the influence of false targets on the previous observations. Figure 9 compares this influence for the extreme-points of our UCAV-attrition scale, that is without attrition ($\varphi/\lambda = 0$) and with high attrition ($\varphi/\lambda = 1$).

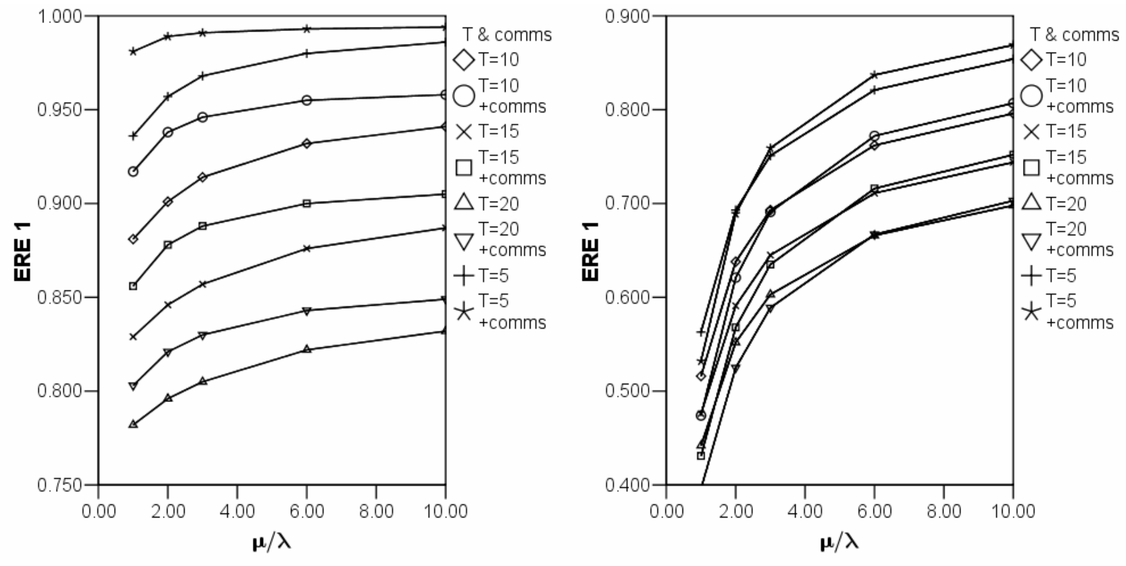

Figure 9 Influence of detection, attack, vulnerability, and coordination on ERE 1:
Left: $\varphi/\lambda = 0$, 10 UCAVs, 4 valuable targets, ADP
Right: $\varphi/\lambda = 1$, 10 UCAVs, 4 valuable targets, ADP

Again, the initial findings are supported. In the case of no attrition, the attack is always more effective when there is full coordination among the UCAVs. Since the UCAVs are not threatened, the rejection of a valuable target due to attack coordination does not imply the risk of removal. In the case where the UCAVs' attrition rate is compatible with their detection rate this may not be so. As the ratio (μ/λ) between the attack rate and the detection rate decreases (attack time gets longer compared to the detection time) the effectiveness of UCAVs' coordination decreases to the point that it becomes counter-effective. Note that the break-even point increases and shifts to higher ratios (μ/λ) with increasing number of false (non-valuable) targets *T-M*. This explains as follows: Every detection process with imperfect specificity $(q_2 < 1)$ may result in erroneous attacks. Coordination among UCAVs decreases the attacks on valuable targets that

are already being attacked, and increases the number of detection events. Therefore, with decreasing μ/λ, more detections occur during the time of attacks on valuable targets, which results in more attacks on false targets. This leads to the point that unsuccessfully attacked valuable targets cannot be re-attacked because the UCAVs have been expended on false targets.

Example for small μ/λ: Consider a UCAV which rejects a valuable target because this target has been reported as being attacked. At the next target detection, the UCAV misclassifies a false target and attacks it. In the meantime, the reported attack on the valuable target fails to be successful. This effect is getting smaller with increasing μ/λ due to the decreasing probability of SMT.

c. Influences of Detection, Attrition, and Coordination for Different Numbers of Targets

We will now explore the influence of μ/λ, and φ/λ for different numbers of valuable targets. We compare scenarios with M = 4 and 6 and T = 10.

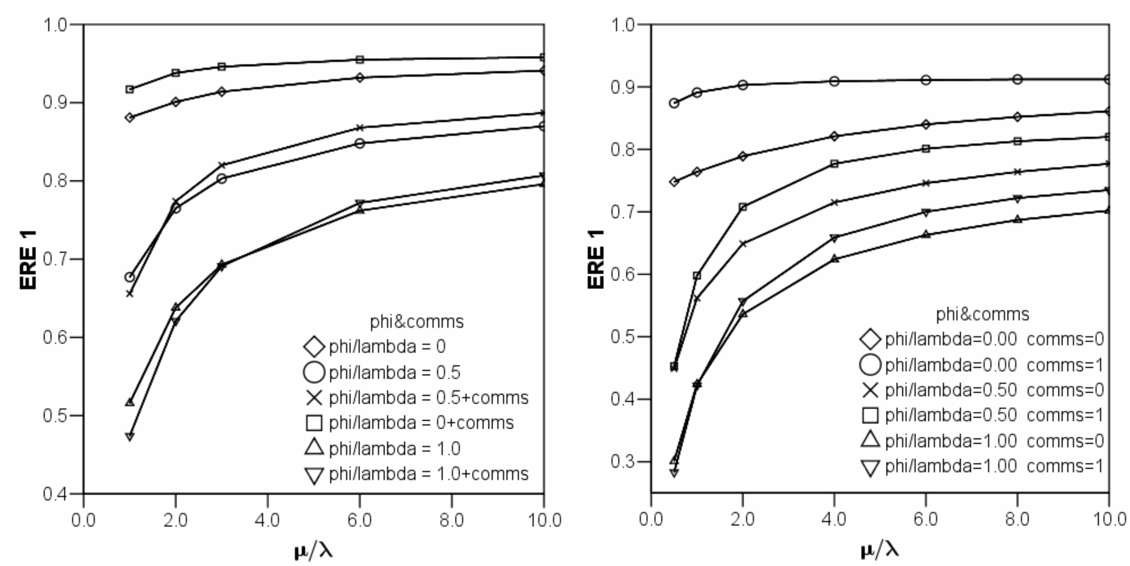

Figure 10 Influence of detection, attack, vulnerability, and coordination on ERE 1:
Left: 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: 10 UCAVs, 6 valuable targets, 10 total targets, ADP

Our previous observations are again confirmed. We further observe that with higher relative numbers of valuable targets, the positive impact of coordination on the expected relative effectiveness is more significant.

d. Time Dependent Impacts and Base Cases for Sensitivity Analysis

Two base cases of combinations of μ/λ *and* φ/λ are now defined for further sensitivity analysis. The first base case, $\mu/\lambda=1$, represents situations with strong impacts of the detection frequency and attack duration on ERE-1. The second case characterizes the transition point from moderate to weak impacts of μ/λ on ERE-1. Following the findings in this chapter, we select $\mu/\lambda=4$. In both cases we choose a moderate UCAV attrition, $\varphi/\lambda=0.1$, that means, the average lifespan of a UCAV is 10 times longer than it takes for a UCAV to find a single target in the target area.

2. Sensitivity Analysis with Strong and Moderate Impacts of μ/λ

The following sensitivity analysis is with respect to the aforementioned two base cases. Base case "A" represents situations with strong influences of SMT and moderate attrition ($\mu/\lambda=1$, $\varphi/\lambda=0.1$) and base case "B" represents situations with moderate influence of SMT. In both base cases, the sensitivity analysis is performed with respect to the assumed design point (ADP, see above).

a. Influence of Classification Capabilities

The target classification capabilities comprise classification sensitivity (q_1) and specificity (q_2). We will now compare the sensitivity of these parameters at the two base cases.

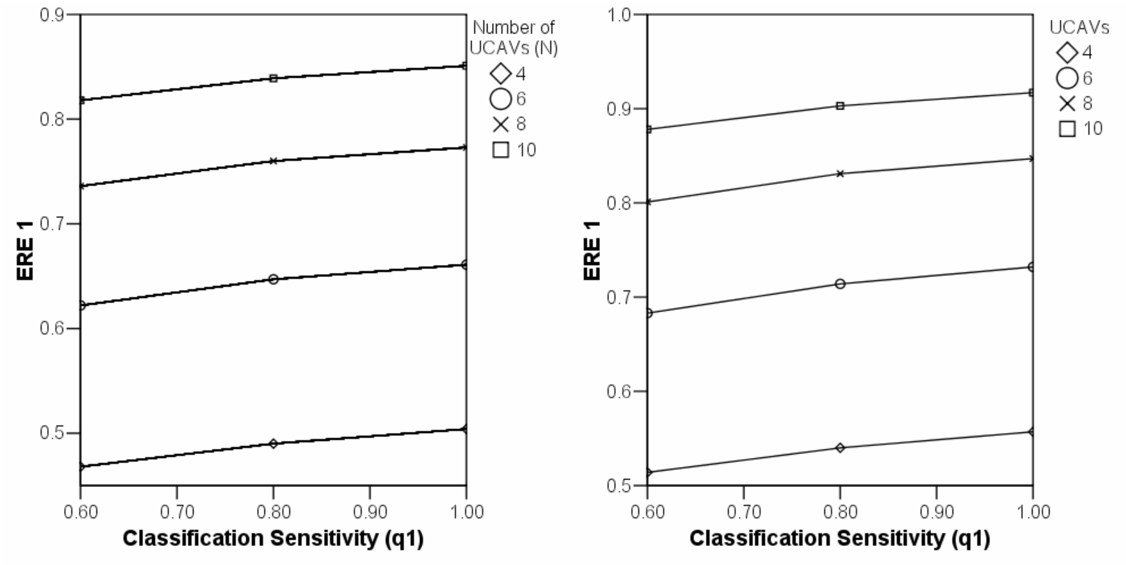

Figure 11 Influence of Classification Sensitivity (q_1) on ERE-1:
Left: $\mu/\lambda=1$, 4 valuable targets, 10 total targets, ADP
Right: $\mu/\lambda=4$, 4 valuable targets, 10 total targets, ADP

The impact of changes of the classification sensitivity (q_1) on the expected relative effectiveness is similar for both base cases. ERE-1 increases nearly linearly by 2% with an 20% increase of q_1. This observation is largely independent of the number of UCAVs.

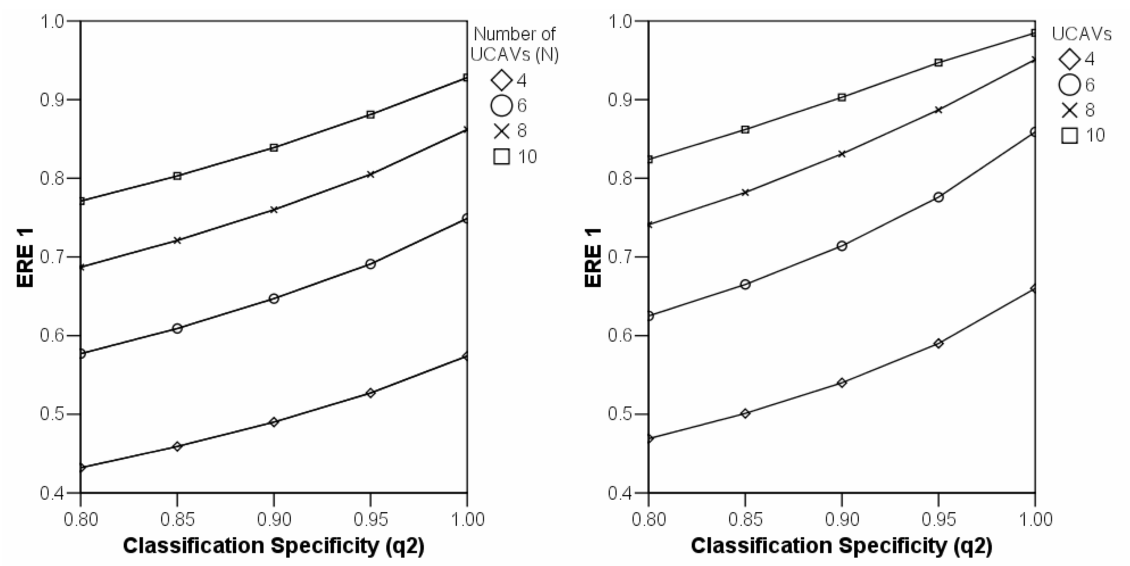

Figure 12 Influence of Classification Specificity (q_2) on ERE 1:
Left: $\mu/\lambda=1$, 4 valuable targets, 10 total targets, ADP
Right: $\mu/\lambda=4$, 4 valuable targets, 10 total targets, ADP

In both base cases the impact of the classification specificity on ERE-1 is significantly stronger than the impact of sensitivity. The impact of q_2 in base case *B* is somewhat stronger than in *A*. Figure 13 shows the impact of different combinations of q_1 and q_2 on ERE-1 for scenarios with N = 10 UCAVs attacking T = 10 targets out of which M = 4 are valuable targets. In both cases, the performance enhancing influence of increasing sensitivity is decreasing with increasing specificity. A non intuitive observation is the decreasing expected relative effectiveness with increasing q_1 for perfect specificity, $q_2=1$. This can be explained by the effect of SMT. Lower values for q_1, with more rejections of valuable targets, slow down the attack frequency and act as SMT-inhibitor. Therefore, the performance increases with decreasing classification sensitivity in scenarios with low attrition and high specificity.

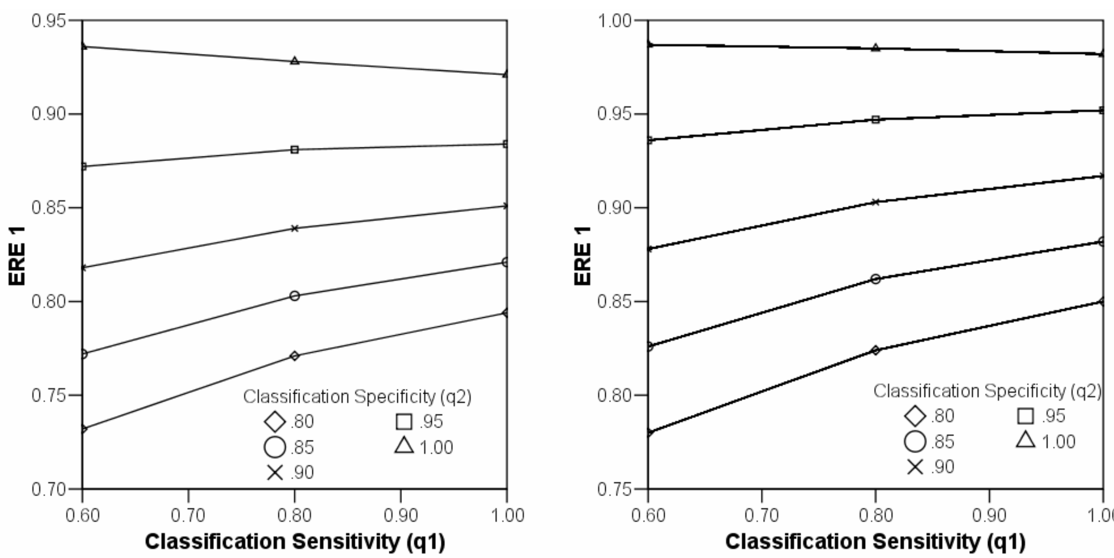

Figure 13 Influence of Classification Sensitivity and of Specificity on ERE 1:
Left: $\mu/\lambda=1$, r=0, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: $\mu/\lambda=4$, r=0, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

Figure 14 shows the same settings with perfect attack coordination. Note that q_1 no longer has a negative impact on ERE-1. On the contrary, the performance of the UCAVs increases slightly with increasing q_1 due to the smaller impact of UCAV attrition with higher q_1.

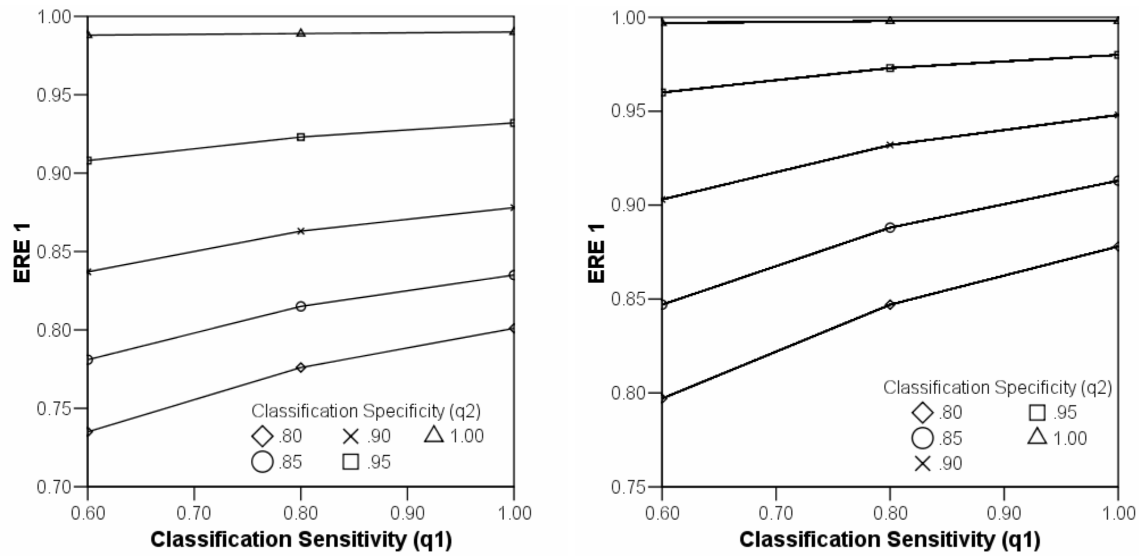

Figure 14 Influence of Classification Sensitivity and of Specificity on ERE 1:
Left: μ/λ=1, r=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ/λ=4, r=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

b. Influence of UCAV Guidance and Warhead Effectiveness

For the SSKP, a strong influence on the expected relative effectiveness in both base cases is observed.

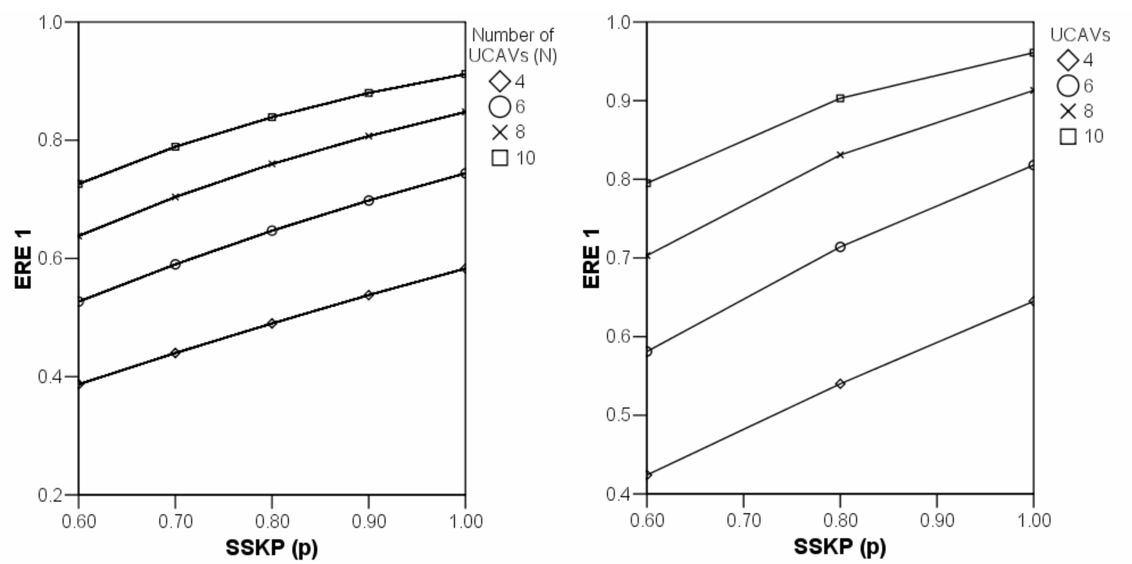

Figure 15 Influence of SSKP (p) on ERE 1:
Left: μ/λ=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ/λ=4, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

The smaller the SSKP, the higher is the sensitivity of ERE-1 to it. These observations for the impact of the SSKP are also found valid for cases of perfect coordination (*r = 1*).

c. Influence of Attack Coordination

Figure 16 shows the effect of the coordination capability among UCAVs.

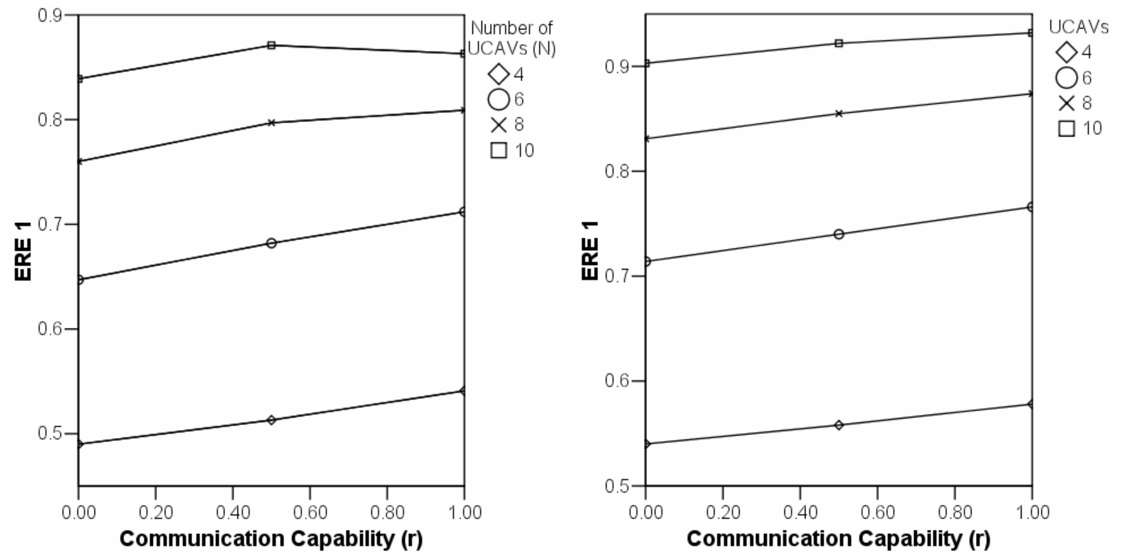

Figure 16 Effect of Coordination (*r*) on ERE 1:
Left: μ/λ=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ/λ=4, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

At high numbers of UCAVs and a strong effect of SMT ($\mu/\lambda=1$), communication decreases performance. Figure 17 shows the dependency of the effect of coordination level, *r*, and the classification specificity on ERE-1.

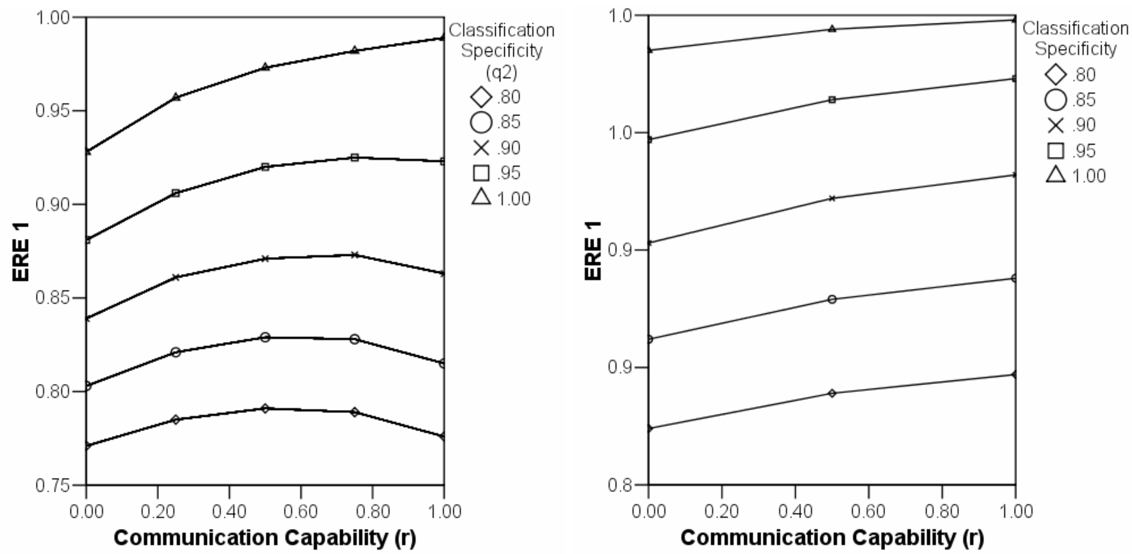

Figure 17 Influence of Coordination and BDA on ERE 1:
Left: μ/λ=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ/λ=4, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

Clearly, the performance decreasing effect of communication at ($\mu/\lambda=1$) is amplified with decreasing classification specificity, q_2. Note the negative gradient of ERE-1 in base case *A* ($\mu/\lambda=1$) and classification specificity smaller than 0.95 ($q_2<0.95$). In this situation, there is an optimum value, $r^* \neq \{0,1\}$, of the communication probability for which ERE-1 is maximal. Note that this counter-intuitive result does not apply to base case *B*. These results demonstrate once again the tradeoff among the level of coordination, the relation between the detection and attack times, the BDA capabilities and the UCAVs' vulnerability.

d. Influence of the Detection Rate

The impact of varying the detection rate, λ, for 10 UCAVs, 4 valuable targets, and 6 false targets (10 total targets) is now examined. The impact on the engagement performance is displayed for selected values of attack durations, attrition rates, BDA parameters and coordination capabilities:

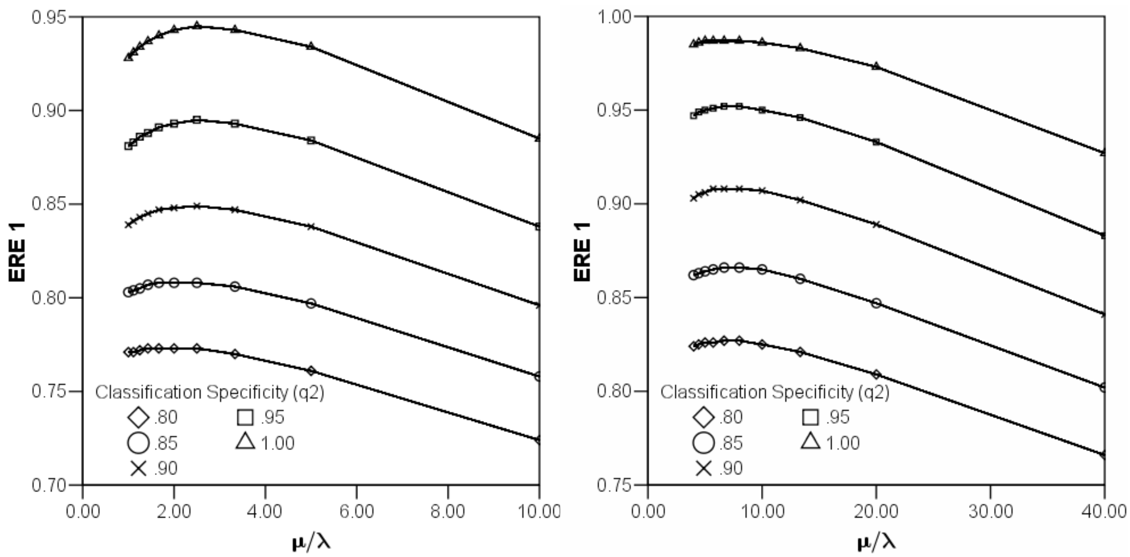

Figure 18	Influence of Detection Rate and BDA (without coordination) on ERE 1:
Left: μ=1, φ=0.1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ=4, φ=0.1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

Again, the tradeoff effect of the different performance-decreasing factors can be observed. At smaller detection rates, UCAV attrition decreases performance, while at higher detection frequencies SMT decreases performance.

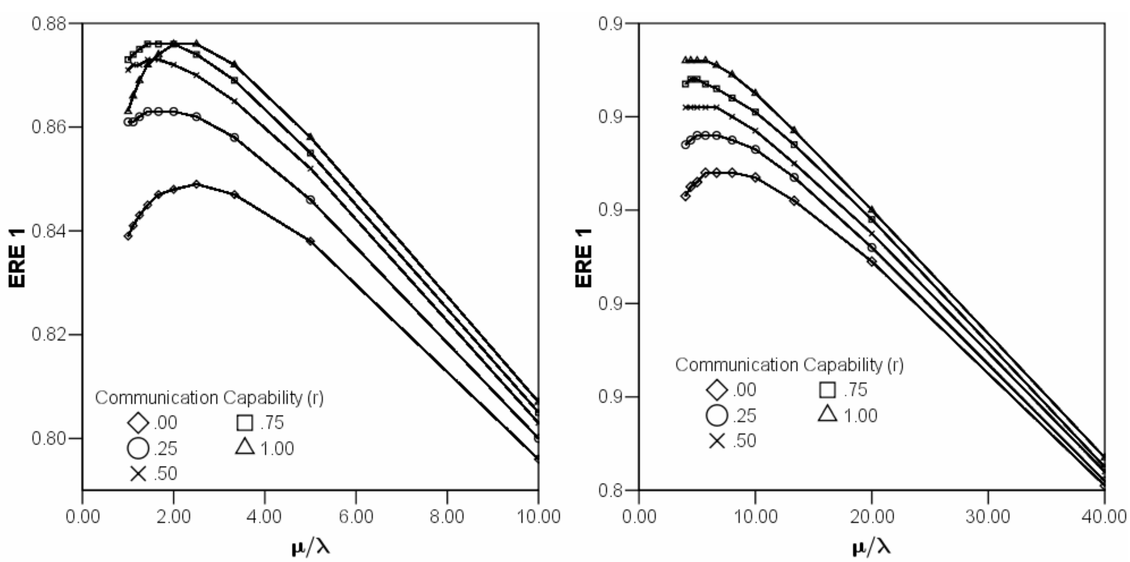

Figure 19	Influence of Detection Rate and Coordination on ERE 1:
Left: μ=1, φ=0.1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: μ=4, φ=0.1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

Figure 19 shows the impact of the average detection rate for different communication qualities on ERE-1 at the ADP. A counterintuitive observation is the strong drop in engagement performance for perfect communication. This phenomenon has already been explained above as a combination of imperfect BDA and SSKP (i.e., $q_2<1$ *and* $p<1$).

e. Influence of the UCAV Attrition Rate

The impact of the UCAVs' attrition rate on ERE-1 is displayed in Figure 20 for different values of coordination levels.

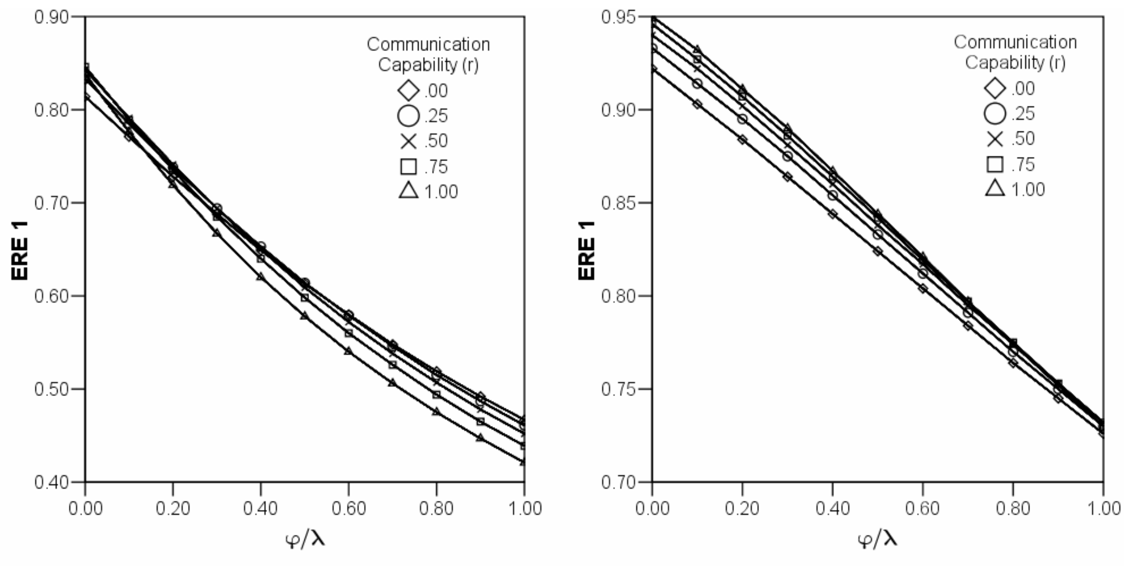

Figure 20 Influence of Attrition Rate and Coordination on ERE 1:
Left: $\mu/\lambda=1$, 10 UCAVs, 4 valuable targets, 10 total targets, ADP
Right: $\mu/\lambda=4$, 10 UCAVs, 4 valuable targets, 10 total targets, ADP

The graphs show that the expected outcome of the attack is very sensitive to the UCAV's attrition rate within the assumed parameter ranges. The graphs show that communication capability does not compensate for deficiencies in vulnerability.

f. *Influence of the Number of False Targets*

The number of false targets (false targets = initial non-valuable targets: *T*-*M*) and the classification specificity are tightly connected in their impact on the engagement effectiveness. Figure 21 displays and compares these factors in the two base cases.

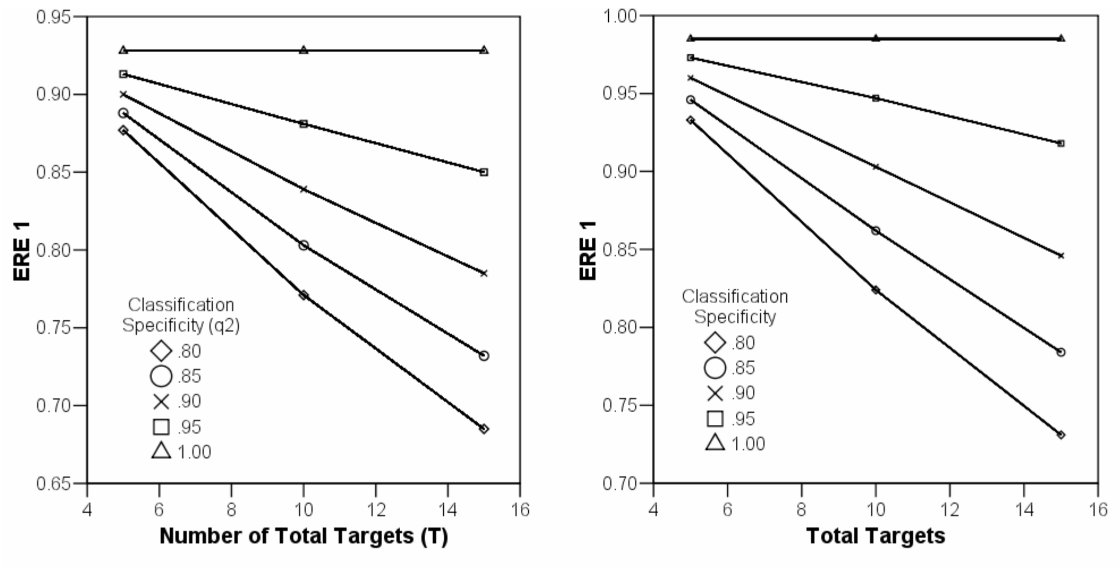

Figure 21 Influence of False Targets and BDA on ERE 1 (Without Coordination):
Left: μ/λ=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP, r=0
Right: μ/λ=4, 10 UCAVs, 4 valuable targets, 10 total targets, ADP, r=0

Clearly, the number of false targets does not matter for perfect specificity. As q_2 decreases, the negative effect of increasing numbers of non-valuable targets becomes more significant. The different results for ERE-1 in Figure 22 show the impact of attack coordination to compensate SMT effects.

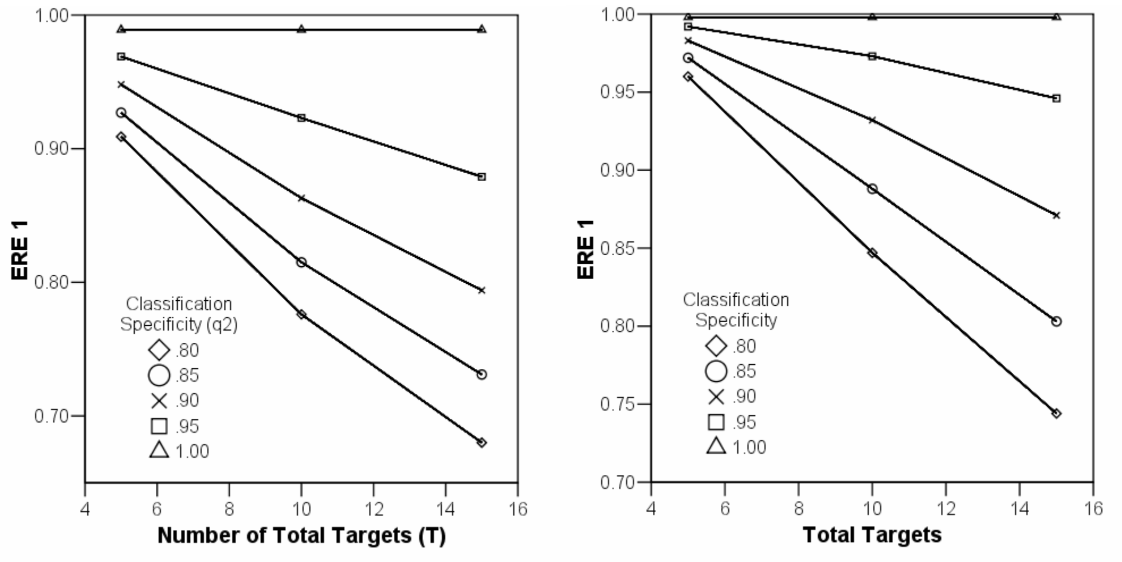

Figure 22 Influence of False Targets and BDA on ERE 1 (With Coordination):
Left: μ/λ=1, 10 UCAVs, 4 valuable targets, 10 total targets, ADP, r=1
Right: μ/λ=4, 10 UCAVs, 4 valuable targets, 10 total targets, ADP, r=1

3. Operational Considerations

An important operational planning problem is to determine the number of UCAVs that are necessary to accomplish mission success. The following example demonstrates an analysis of this problem. To emphasize the operational character of this example, we scope this analysis to factors that are considered (by war-fighters) for decision making (N, M, T, λ, r) for a fixed UCAV design (q_1, q_2, p) and fixed average attack duration and attrition rate (μ, φ).

We assume $q_1=0.8$, $q_2=0.9$, $p=0.8$, $r=0$ for the basics design, $r=1$ if a communication module is included and not jammed. We further assume an average attack time of $1/\mu=0.5$ *minutes*, attrition rate of $\varphi=0.1$ min^{-1} and detection rate of $\lambda=[0.2,...,1]$ min^{-1} ($\mu/\lambda=[2,\dots,10]$; $\varphi/\lambda=0.1$). We assume that based on intelligence reports there are 10 targets in the target area, out of which 2 to 6 are valuable targets.

The engagement planning process may include the following nine questions that can be answered with the corresponding graphs.

(1) & (2) How many UCAVs do I need to destroy all of the targets with a probability of at least 50% and what is the expected time of the engagement?

Observe in Figure 23 that, under given design and scenario conditions, the effort to destroy all targets is fairly high. For example, to destroy 4 valuable targets with a probability of 50%, 10 UCAVs have to be deployed. The average duration of the engagement shows the two reasons for fast finishing scenarios when either (i) a small number of valuable targets is quickly destroyed by a high number of UCAVs (at *N>5, M=2*), or (ii) a small number of UCAVs is quickly expanded on a larger number of targets (at *N=10, M=6*).

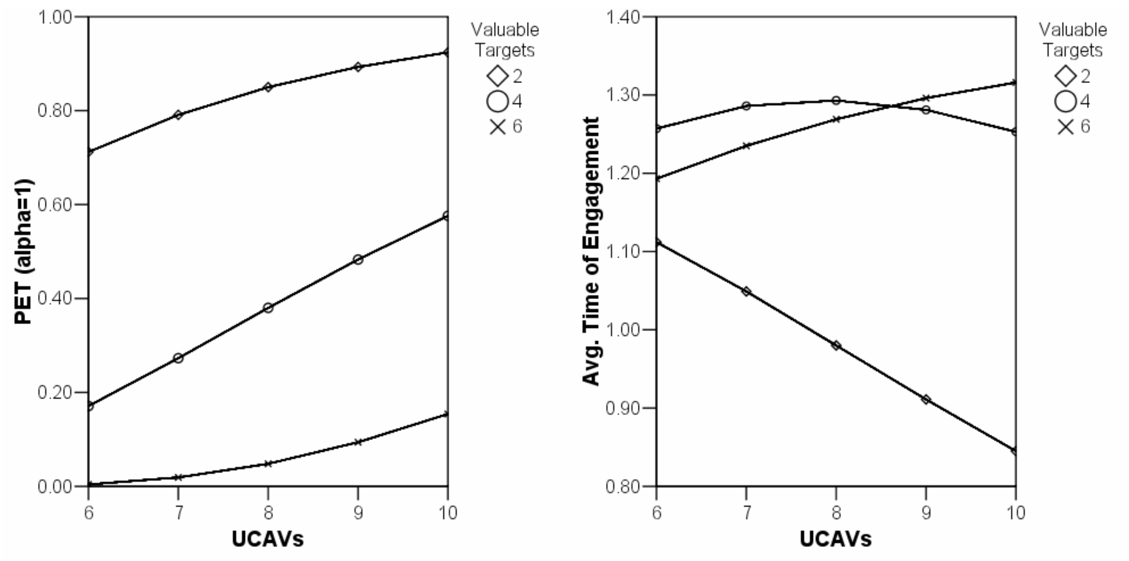

Figure 23 Probability to kill all valuable targets and average engagement duration
Parameters: $\lambda=1$, $\mu=2$, $\varphi=0.1$, $p=0.8$, $q_1=0.8$, $q_2=0.9$, $r=0$, $T=10$

(3) & (4) What percentage of valuable targets is going to be destroyed with how many UCAVs and what is the change in performance without attrition?

Figure 24 shows the percentage of destroyed valuable targets dependent on the employed UCAVs and valuable targets in the scenario of 10 targets in total with and without attrition.

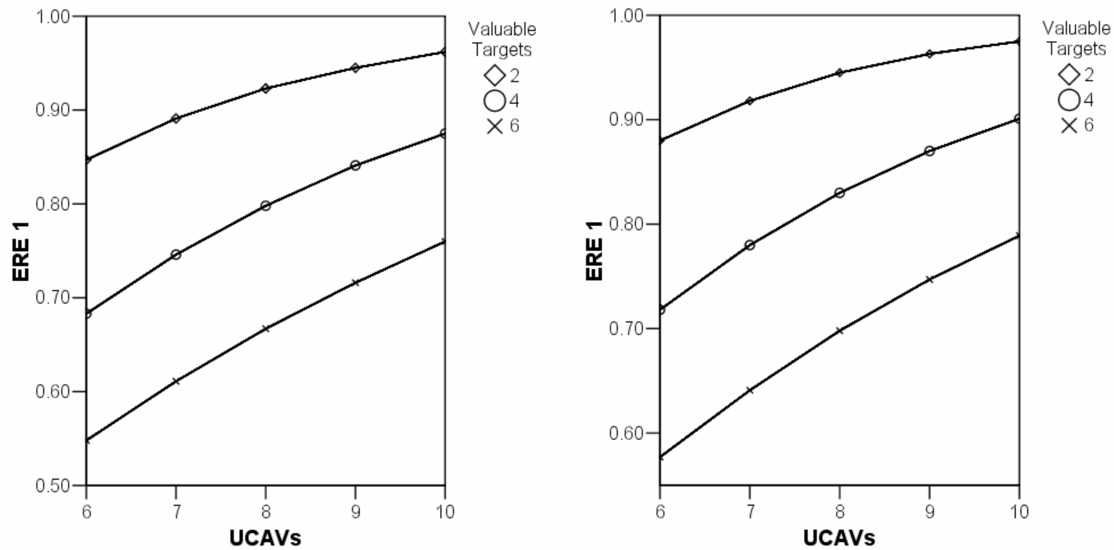

Figure 24 Fraction of killed valuable targets with and without attrition
Parameters: $\lambda=1$, $\mu=2$, $p=0.8$, $q_1=0.8$, $q_2=0.9$, $r=0$, $T=10$
Left: Attrition Rate $\varphi=0.1$; Right: No Attrition, $\varphi=0$

Clearly, attrition is not an important factor in this scenario, because the absence of attrition only provides a 3% increase of ERE-1in this scenario. Stealth considerations or other efforts to decrease UCAV-vulnerability are therefore not necessary.

(5) & (6) How many UCAVs are still (on average) loitering when the mission is accomplished and what percentage of the UCAVs is effective?

Figure 25 shows the average percentage of unexpended UCAVs at the end of the scenario. Recall that the end of the scenario is when either all UCAVs are expended or when all valuable targets are destroyed. ERE-2 in Figure 25 shows the relative efficiency of the engagement, that is, how many valuable targets are killed by one UCAV. With increasing numbers of engaging UCAVs the engagement efficiency decreases nearly linear and at a constant rate for different numbers of initial valuable targets.

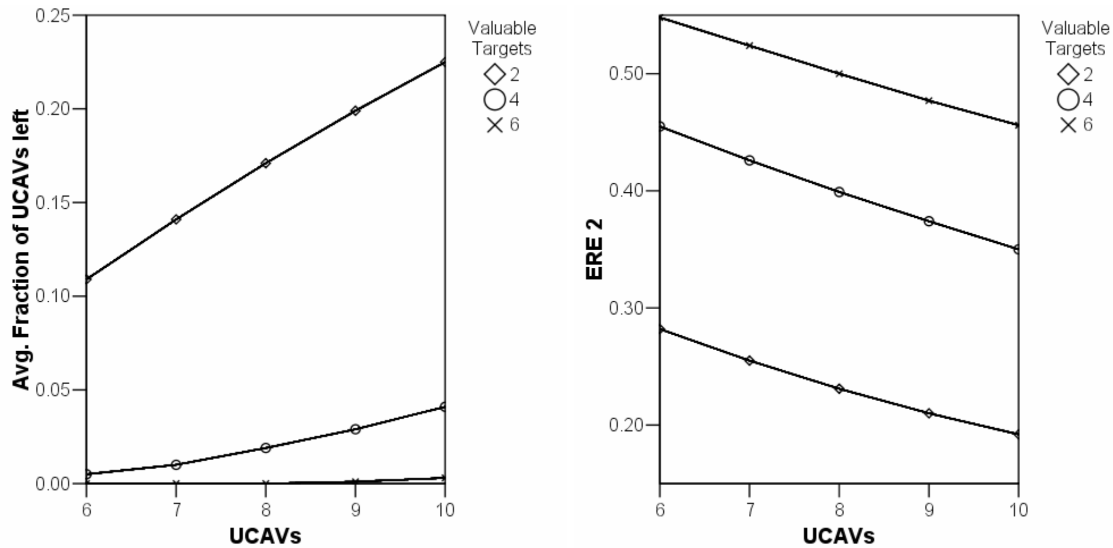

Figure 25 Fraction of not expanded UCAVs and Engagement Efficiency
Parameters: $\lambda=1$, $\mu=2$, $\varphi=0.1$, $p=0.8$, $q_1=0.8$, $q_2=0.9$, $r=0$, $T=10$

(7) & (8) Is it useful in this scenario to engage with UCAVs that are equipped with attack coordination and what is the effect of deviations of the assumed average detection rate? (we assume 4 valuable targets and a total of 10 targets)

Figure 26 shows that in this scenario any improvement of attack coordination capabilities results in higher engagement performance. The impact of attack coordination on ERE-1 is more important for smaller numbers of UCAVs. However, the implementation of perfect attack coordination has roughly, for all *N*, the same effect on ERE-1 as the increase of the number of UCAVs by one in the scenario. ERE-1 shows only small sensitivity regarding to the detection frequency (about 2% over the assumed range of λ). The optimal performance for the assumed detection frequency is at $\lambda=0.4\ min^{-1}$ $(\mu/\lambda=5)$ with slightly decreasing ERE-1 to higher detection rates and stronger decreasing ERE-1 to lower detection rates.

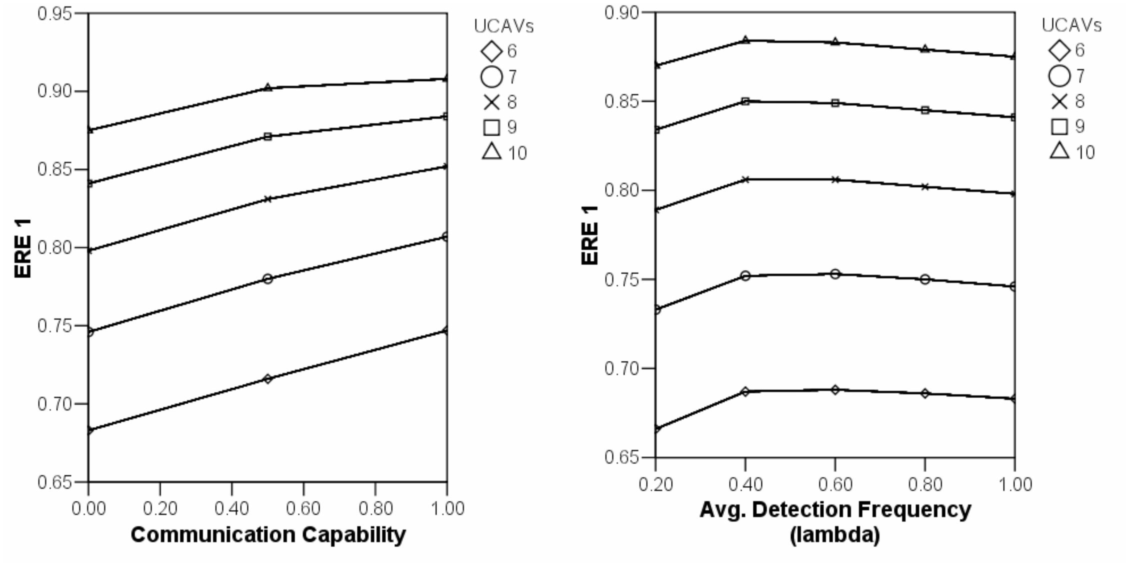

Figure 26 Avg. fraction of killed targets, communication and detection rate
Parameters:, $\mu=2$, $\varphi=0.1$, $p=0.8$, $q_1=0.8$, $q_2=0.9$, $T=10$, $M=4$
Left: Impact of attack coordination by communication, r, for $\lambda=1$
Right: Impact of different average detection rates, λ, for $r = 0$

(9) What impact do higher numbers of false targets have on the mission success? (we assume 4 valuable targets)

Figure 27 shows the strong impact of the presence of false targets (*T-M*) on the engagement effectiveness. A decrease of roughly 20% in ERE-1 is created by increasing the total number of targets from 10 to 30. This shows that even if the classification specificity with $q_2=0.9$ seems high, improvements for q_2 are necessary for scenarios with high false target density. An operational approach to this problem is to choose engagement conditions (i.e.-day/night), where greater differences of target signatures between valuable targets and false targets hold better BDA specificity.

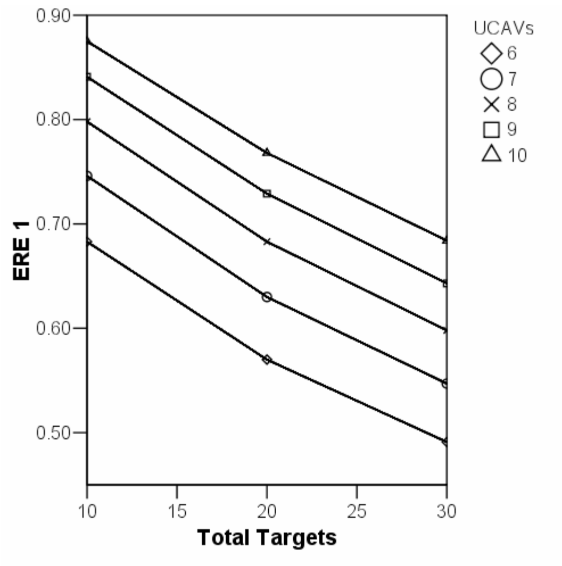

Figure 27 Avg. fraction of killed valuable targets, total targets, and UCAVs
Parameters: λ=1, μ=2, φ=0.1, p=0.8, q_1=0.8, q_2=0.9, r=0, M=4

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VI. CONCLUSIONS AND FUTURE WORK

A. MODEL

The main contribution of this thesis is a new continuous time Markov Model, which is utilized to analyze swarm engagements of UCAVs on targets. The model is implemented in Java-based software that generates the state-space, computes the transition probabilities and derives values of key MOEs. The model and its implementation demonstrate an effective and efficient analytic alternative for commonly used Monte-Carlo simulations. The model handles large scale state-spaces that correspond to realistic combat situations.

The model is tractable, has fast run times, produces the desired results (MOEs) in one run, and has the potential to be utilized in optimization (NLP) analysis. The model also has the flexibility to adapt to different assumptions while still using the initial state space description. Model extensions and modifications can take account of new modeling requirements, such as multiple target types, while still using the same systematic modeling approach.

B. PERFORMANCE FACTORS

The model describes the impact of four main performance factors that affect the outcome of the engagement: (i) multi-kill due to simultaneous targeting and attacks, (ii) multi-kill due to misclassification (imperfect BDA), (iii) ineffective impacts on targets, and (iv) UCAV attrition due to technical failure, accidents or interception. These factors are analyzed with respect to design and operational parameters such as detection rate, attack rate and number of targets. It was found that different performance factors dominate others, leading to tradeoff relations among the various factors at different design points.

1. Multi-Kill

a. Multi-Kill due to Simultaneous Multi Targeting (SMT)

Recall that SMT describes the effect that a target, that is under attack, is detected and investigated (targeted) by other UCAVs. Depending on the result of the classification, this can lead to simultaneous attacks of multiple UCAVs on the target. This factor is important if the attack durations are short compared to the time to detection. If the two times are approximately the same, the SMT has a performance decreasing influence of about 5% for reasonable parameter values. The implementation of attack coordination eliminates this impact of SMT. However, attack coordination amplifies attrition effects and the impact of multi-kill due to imperfect classification.

b. Multi-Kill due to Misclassification (BDA)

This factor gains importance for lower classification specificities and higher numbers of false targets. For the assumed design point (ADP) of specificity q_2 = 0.9 and equal numbers of valuable and false targets (*T*-*M*), the performance-decreasing impact of misclassification is about 10-15% compared to perfect specificity. If the ratio between the valuable and false targets changes from 1 to 0.5, then the engagement performance drops by 5% for the ADP and by 10% for q_2 = 0.8.

2. UCAV Attrition

This factor has a strong performance decreasing influences for long attack times, long detection times and low classification sensitivity (q_1). An attrition rate that is about 10% of the detection rate has a performance decreasing influence of about 5% for the ADP when compared to the case of no attrition. Decreasing classification sensitivity augments attrition effects due to longer loitering times. Attrition is also a significant factor in the presence of attack coordination in combination with long attack times and high detection rates. Here, the performance decreasing effect of attrition is amplified by attack coordination.

3. Attack Effectiveness

Lower SSKP, has a strong influence in cases where a second attack on the target is unlikely. This occurs for small numbers of UCAVs compared to the number of targets. Attack effectiveness is also important in the presence of attack coordination in combination with (i) high attrition rates and long attack times and/or (ii) low classification specificity and many false targets. For the assumed design point, SSPK at $p = 0.8$, the performance-decreasing impact of imperfect SSKP is about 10% compared to perfect SSKP.

C. DESIGN PROPERTIES AND INFLUENCE FACTORS

1. Influence of Classification

It was shown that at design points of interest, the impact of classification specificity (q_2) is more important than classification sensitivity (q_1). Also, with increasing numbers of false targets and in scenarios with strong SMT combined with attack coordination, specificity gains additional importance as a performance influencing parameter. The performance always increases with the classification (BDA) specificity. Classification sensitivity influences the number of detection occurrences and therefore the inter-attack time by the likelihood to accept a detected valuable target. It gains more importance for design points with lower specificities and high attrition rates, where a rejection of a valuable target holds a high risk of loosing the UCAV to attrition or to an attack on a non-valuable target.

2. Influence of Communications

Depending on the design point, the presence of communication for attack coordination, as implemented in the model, can have performance enhancing or decreasing properties. At certain design points, the best engagement results are obtained with partial communication ($0 < r < 1$).

Communication increases performance only in SMT situations, especially for low attrition rates, high classification specificity and high SSKP. Attack coordination prevents the waste of ammunition due to simultaneous attacks on the same target. In scenarios

with low attrition and high specificity, targets attacked without success can be attacked again later on. Decreases in engagement performance as a result of attack coordination can be observed for SMT situations with high attrition and/or low classification specificity in combination with decreasing SSKP. The reason is this: When valuable targets are rejected due to attack coordination, but the attacks do not result in certain kills, UCAVs are expended on (i) attacks on false targets or (ii) attrition. Later, further attacks on targets cannot be conducted because all UCAVs are expended. This means that good design features are further improved by attack coordination, while for less effective design points with SMT effects, communication can actually decrease the performance. This is a counter-intuitive and important result of the analysis.

D. IMPLICATIONS AND RECOMMENDATIONS

1. Design Considerations

The findings allow general conclusions about UCAV designs:

- The most important UCAVs' design factors in the explored parameter range are SSKP and classification specificity. Designs have to concentrate primarily on minimizing (i) attacks on false targets and (ii) ineffective hits.

- In case of equal average attack and detection times and the presence of attack coordination, it is important to tailor the attack coordination for the specific UCAV design and scenario to obtain optimal performance. Depending on the scenario parameters and the design parameters, attack coordination must account for the possibility of letting a specific number of UCAVs simultaneously attack the same target. This can be accomplished by adjusting the value of the coordination parameter r.

- It may be useful to introduce adjustable, random attack delays after classification of a target. This may reduce SMT effects absent attack coordination. This feature would represent an additional target observation state with repeated classification before the actual attack after the random time period occurs, and would therefore basically extend the detection time. However, this is only recommended for sce-

narios with low attrition rates. Another approach to dealing with SMT is the implementation of continuous classification during the attack phase and the abortion of the attack, with return to the search mode if the target status changes.

- For new UCAV designs, this model can be used to explore globally optimal parameter combinations. Sensitivity analysis or local optimization starting at the current design point can be conducted for design enhancements.

2. Operational Considerations

In the following, it is assumed that the UCAV design is fixed and only the engagement planning can be altered.

If the UCAVs do not possess attack coordination, and the analysis shows strong impacts of multi-kill due to SMT, engagement tactics in waves, rather than simultaneous swarm, should be considered. Other tactical solutions include enlarging the target area to reduce the detection rate and therefore SMT, or assigning separate areas to the UCAVs. The latter, however, means losing the benefits of swarm attacks (area-redundancy, low organizational efforts).

If the UCAVs possess the capability for attack coordination, it is important to adjust communication or deactivate communication for cases where attack coordination leads to decreased performance in the scenario. As analyzed above, this situation is possible for scenarios with SMT (relatively long attack times compared to detection times) and small SSKP in combination with (i) small classification specificity and many false targets, and/or (ii) high attrition rates.

E. FUTURE WORK

Our model is restricted to one type of targets. In real life scenarios, there are different target types with different signatures. Subsequent work might include the development and implementation of a model modification for multi-target type scenarios.

Also, this model assumes low altitude attacks and can therefore justify exponentially distributed detection ranges and times. For higher loitering altitudes, the time it

takes the UCAV to reach the surface must be considered. This requires model modifications for attack times with different distributions containing constant and random elements that would account for (i) attack phases starting at higher altitudes and (ii) for different detection and attack processes.

The development and software implementation of an optimization shell for the Markov model is capable of providing solutions for optimal cost-performance considerations. This process could start from current UCAV design points to suggest design enhancements for fixed budgets.

Data analysis on a large scale can explore multi-parameter cost-performance optima. A suggested analytic design for this purpose is the Latin Hypercube (Cioppa, 2002).

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